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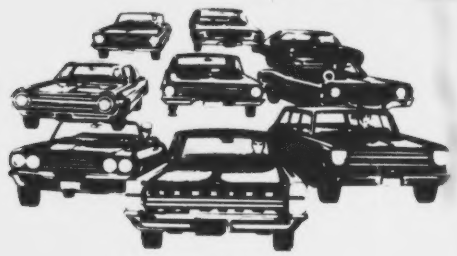

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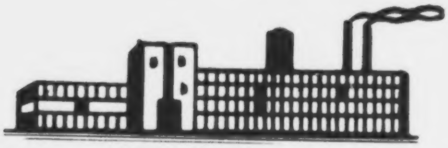

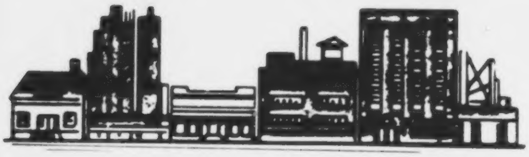

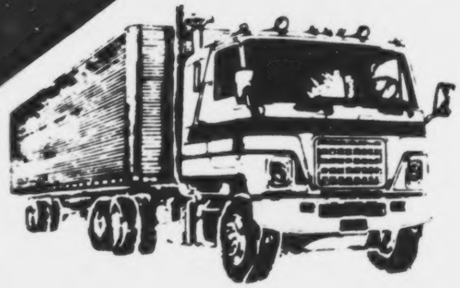

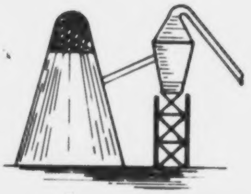

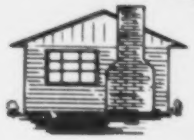

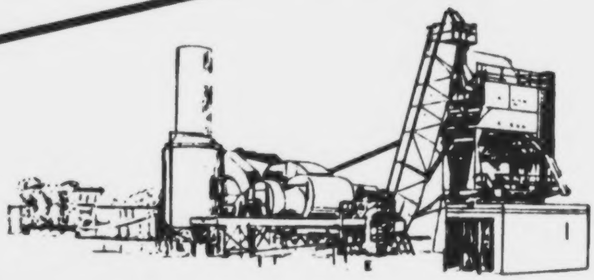

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COMPILATION

OF

AIR POLLUTANT EMISSION FACTORS

Third Edition

(Including Supplements 1-7)

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Air and Waste Management
Office of Air Quality Planning and Standards
Research Triangle Park, North Carolina 27711

August 1977

This report is published by the Environmental Protection Agency to report information of general interest in the field of air pollution. Copies are available free of charge to Federal employees, current contractors and grantees, and nonprofit organizations—as supplies permit—from the Library Services Office, Environmental Protection Agency, Research Triangle Park, North Carolina 27711. This document is also available to the public for sale through the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C.

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PREFACE

This document reports data available on those atmospheric emissions for which sufficient information exists to establish realistic emission factors. The information contained herein is based on Public Health Service Publication 999-AP-42, *Compilation of Air Pollutant Emission Factors*, by R.L. Duprey, and on three revised and expanded editions of *Compilation of Air Pollutant Emission Factors* that were published by the Environmental Protection Agency in February 1972, April 1973, and February 1976. This document is the third edition and includes the supplements issued in July 1973, September 1973, July 1974, January 1975, December 1975, April 1976, and April 1977 (see page iv). It contains no new information not already presented in the previous issuances.

Chapters and sections of this document have been arranged in a format that permits easy and convenient replacement of material as information reflecting more accurate and refined emission factors is published and distributed. To speed dissemination of emission information, chapters or sections that contain new data will be issued—separate from the parent report—whenever they are revised.

To facilitate the addition of future materials, the punched, loose-leaf format was selected. This approach permits the document to be placed in a three-ring binder or to be secured by rings, rivets, or other fasteners; future supplements or revisions can then be easily inserted. The lower left- or right-hand corner of each page of the document bears a notation that indicates the date the information was issued.

Information on the availability of future supplements to *Compilation of Air Pollutant Emission Factors* can be obtained from the Environmental Protection Agency, Library Services, MD-35, Research Triangle Park, N.C. 27711 (Comm. Telephone: 919-541-2777, FTS: 629-2777).

Comments and suggestions regarding this document should be directed to the attention of Director, Monitoring and Data Analysis Division, Office of Air Quality Planning and Standards, Environmental Protection Agency, Research Triangle Park, N.C. 27711.

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Because this document is a product of the efforts of many individuals, it is impossible to acknowledge each person who has contributed. Special recognition is given to Environmental Protection Agency employees in the Requests and Information Section, National Air Data Branch, Monitoring and Data Analysis Division, for their efforts in the production of this work. Bylines identify the contributions of individual authors who revised specific sections and chapters.

PUBLICATIONS IN SERIES

Issuance	Release Date
Compilation of Air Pollutant Emission Factors (second edition)	4/73
Supplement No. 1	7/73
Section 4.3 Storage of Petroleum Products	
Section 4.4 Marketing and Transportation of Petroleum Products	
Supplement No. 2	9/73
Introduction	
Section 3.1.1 Average Emission Factors for Highway Vehicles	
Section 3.1.2 Light-Duty, Gasoline-Powered Vehicles	
Supplement No. 3	7/74
Introduction	
Section 1.4 Natural Gas Combustion	
Section 1.5 Liquified Petroleum Gas Combustion	
Section 1.6 Wood/Bark Waste Combustion in Boilers	
Section 2.5 Sewage Sludge Incineration	
Section 7.6 Lead Smelting	
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Section 10.2 Pulpboard	
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Section 3.3.3 Gasoline and Diesel Industrial Engines	
Chapter 11 Miscellaneous Sources	
Appendix B Emission Factors and New Source Performance Standards	
Appendix C NEDS Source Classification Codes and Emission Factor Listing	
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Appendix D Projected Emission Factors for Highway Vehicles	

	Issuance	Release Date
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Section 10.4	Woodworking Operations	
Supplement to No. 7		
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Section 4.3	Storage of Petroleum Liquids	
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ABSTRACT

Emission data obtained from source tests, material balance studies, engineering estimates, etc., have been compiled for use by individuals and groups responsible for conducting air pollution emission inventories. Emission factors given in this document, the result of the expansion and continuation of earlier work, cover most of the common emission categories: fuel combustion by stationary and mobile sources; combustion of solid wastes; evaporation of fuels, solvents, and other volatile substances; various industrial processes; and miscellaneous sources. When no source-test data are available, these factors can be used to estimate the quantities of primary pollutants (particulates, CO, SO_2, NO_x, and hydrocarbons) being released from a source or source group.

Key words: fuel combustion, stationary sources, mobile sources, industrial processes, evaporative losses, emissions, emission data, emission inventories, primary pollutants, emission factors.

1. EXTERNAL COMBUSTION SOURCES

External combustion sources include steam-electric generating plants, industrial boilers, commercial and institutional boilers, and commercial and domestic combustion units. Coal, fuel oil, and natural gas are the major fossil fuels used by these sources. Other fuels used in relatively small quantities are liquefied petroleum gas, wood, coke, refinery gas, blast furnace gas, and other waste- or by-product fuels. Coal, oil, and natural gas currently supply about 95 percent of the total thermal energy consumed in the United States. In 1970 over 500 million tons (454×10^6 MT) of coal, 623 million barrels (99×10^9 liters) of distillate fuel oil, 715 million barrels (114×10^9 liters) of residual fuel oil, and 22 trillion cubic feet (623×10^{12} liters) of natural gas were consumed in the United States.[1]

Power generation, process heating, and space heating are some of the largest fuel-combustion sources of sulfur oxides, nitrogen oxides, and particulate emissions. The following sections present emission factor data for the major fossil fuels – coal, fuel oil, and natural gas – as well as for liquefied petroleum gas and wood waste combustion in boilers.

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1.1 BITUMINOUS COAL COMBUSTION

Revised by Robert Rosensteel
and Thomas Lahre

1.1.1 General

Coal, the most abundant fossil fuel in the United States, is burned in a wide variety of furnaces to produce heat and steam. Coal-fired furnaces range in size from small handfired units with capacities of 10 to 20 pounds (4.5 to 9 kilograms) of coal per hour to large pulverized-coal-fired units, which may burn 300 to 400 tons (275 to 360 MT) of coal per hour.

Although predominantly carbon, coal contains many compounds in varying amounts. The exact nature and quantity of these compounds are determined by the location of the mine producing the coal and will usually affect the final use of the coal.

1.1.2 Emissions and Controls

1.1.2.1 Particulates[1] - Particulates emitted from coal combustion consist primarily of carbon, silica, alumina, and iron oxide in the fly-ash. The quantity of atmospheric particulate emissions is dependent upon the type of combustion unit in which the coal is burned, the ash content of the coal, and the type of control equipment used.

Table 1.1-1 gives the range of collection efficiencies for common types of fly-ash control equipment. Particulate emission factors expressed as pounds of particulate per ton of coal burned are presented in Table 1.1-2.

1.1.2.2 Sulfur Oxides[11] - Factors for uncontrolled sulfur oxides emission are shown in Table 1-2 along with factors for other gases emitted. The emission factor for sulfur oxides indicates a conversion of 95 percent of the available sulfur to sulfur oxide. The balance of the sulfur is emitted in the fly-ash or combines with the slag or ash in the furnace and is removed with them.[1] Increased attention has been given to the control of sulfur oxide emissions from the combustion of coal. The use of low-sulfur coal has been recommended in many areas; where low-sulfur coal is not available, other methods in which the focus is on the removal of sulfur oxide from the flue gas before it enters the atmosphere must be given consideration.

A number of flue-gas desulfurization processes have been evaluated; effective methods are undergoing full-scale operation. Processes included in this category are: limestone-dolomite injection, limestone wet scrubbing, catalytic oxidation, magnesium oxide scrubbing, and the Wellman-Lord process. Detailed discussion of various flue-gas desulfurization processes may be found in the literature.[12,13]

1.1.2.3. Nitrogen Oxides[1,5] - Emissions of oxides of nitrogen result not only from the high temperature reaction of atmospheric nitrogen and oxygen in the combustion zone, but also from the partial combustion of nitrogenous compounds contained in the fuel. The important factors that affect NO_x production are: flame and furnace temperature, residence time of combustion gases at the flame temperature, rate of cooling of the gases, and amount of excess air present in the flame. Discussions of the mechanisms involved are contained in the indicated references.

1.1.2.4 Other Gases - The efficiency of combustion primarily determines the carbon monoxide and hydrocarbon content of the gases emitted from bituminous coal combustion. Successful combustion that results in a low level of carbon monoxide and organic emissions requires a high degree of turbulence, a high temperature, and sufficient time for the combustion reaction to take place. Thus, careful control of excess air rates, the use of high combustion temperature, and provision for intimate fuel-air contact will minimize these emissions.

Factors for these gaseous emissions are also presented in Table 1.1-2. The size range in Btu per hour for the various types of furnaces as shown in Table 1.1-2 is only provided as a guide in selecting the proper factor and is not meant to distinguish clearly between furnace applications.

TABLE 1.1-1. RANGE OF COLLECTION EFFICIENCIES FOR COMMON TYPES OF FLY-ASH CONTROL EQUIPMENT[a]

	Range of collection efficiencies, %			
Type of furnace	Electrostatic precipitator	High-efficiency cyclone	Low-resistance cyclone	Settling chamber expanded chimney bases
Cyclone furnace	65 to 99.5[b]	30 to 40	20 to 30	10[b]
Pulverized unit	80 to 99.5[b]	65 to 75	40 to 60	20[b]
Spreader stoker	99.5[b]	85 to 90	70 to 80	20 to 30
Other stokers	99.5[b]	90 to 95	75 to 85	25 to 50

[a] References 1 and 2.

[b] The maximum efficiency to be expected for this collection device applied to this type source.

Table 1.1-2. EMISSION FACTORS FOR BITUMINOUS COAL COMBUSTION WITHOUT CONTROL EQUIPMENT
EMISSION FACTOR RATING: A

Furnace size, 10^6 Btu/hr heat input[a]	Particulates[b]		Sulfur oxides[c]		Carbon monoxide		Hydro-carbons[d]		Nitrogen oxides		Aldehydes	
	lb/ton coal burned	kg/MT coal burned	lb/ton coal burned	kg/MT coal burned	lb/ton coal burned	kg/MT coal burned	lb/ton coal burned	kg/MT coal burned	lb/ton coal burned	kg/MT coal burned	lb/ton coal burned	kg/MT coal burned
Greater than 100[e] (Utility and large industrial boilers)												
Pulverized												
General	16A	8A	38S	19S	1	0.5	0.3	0.15	18	9	0.005	0.0025
Wet bottom	13A[f]	6.5A	38S	19S	1	0.5	0.3	0.15	30	15	0.005	0.0025
Dry bottom	17A	8.5A	38S	19S	1	0.5	0.3	0.15	18	9	0.005	0.0025
Cyclone	2A	1A	38S	19S	1	0.5	0.3	0.15	55	27.5	0.005	0.0025
10 to 100[g] (large commercial and general industrial boilers)												
Spreader stoker[h]	13A[i]	6.5A	38S	19S	2	1	1	0.5	15	7.5	0.005	0.0025
Less than 10[j] (commercial and domestic furnaces)												
Underfeed stoker	2A	1A	38S	19S	10	5	3	1.5	6	3	0.005	0.0025
Hand-fired units	20	10	38S	19S	90	45	20	10	3	1.5	0.005	0.0025

[a] 1 Btu/hr = 0.252 kcal/hr.

[b] The letter A on all units other than hand-fired equipment indicates that the weight percentage of ash in the coal should be multiplied by the value given. Example: If the factor is 16 and the ash content is 10 percent, the particulate emissions before the control equipment would be 10 times 16, or 160 pounds of particulate per ton of coal (10 times 8, or 80 kg of particulates per MT of coal).

[c] S equals the sulfur content (see footnote b above).

[d] Expressed as methane.

[e] References 1 and 3 through 7.

[f] Without fly-ash reinjection.

[g] References 1, 4, and 7 through 9.

[h] For all other stokers use 5A for particulate emission factor.

[i] Without fly-ash reinjection. With fly-ash reinjection use 20 A. This value is not an emission factor but represents loading reaching the control equipment.[1]

[j] References 7, 9, and 10.

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1.2 ANTHRACITE COAL COMBUSTION

revised by Tom Lahre

1.2.1 General[1,2]

Anthracite is a high-rank coal having a high fixed-carbon content and low volatile-matter content relative to bituminous coal and lignite. It is also characterized by higher ignition and ash fusion temperatures. Because of its low volatile-matter content and non-clinkering characteristics, anthracite is most commonly fired in medium-sized traveling-grate stokers and small hand-fired units. Some anthracite (occasionally along with petroleum coke) is fired in pulverized-coal-fired boilers. None is fired in spreader stokers. Because of its low sulfur content (typically less than 0.8 percent, by weight) and minimal smoking tendencies, anthracite is considered a desirable fuel where readily available.

In the United States, all anthracite is mined in Northeastern Pennsylvania and consumed primarily in Pennsylvania and several surrounding states. The largest use of anthracite is for space heating; lesser amounts are employed for steam-electric production, coke manufacturing, sintering and pelletizing, and other industrial uses. Anthracite combustion currently represents only a small fraction of the total quantity of coal combusted in the United States.

1.2.2 Emissions and Controls[2-9]

Particulate emissions from anthracite combustion are a function of furnace-firing configuration, firing practices (boiler load, quantity and location of underfire air, sootblowing, flyash reinjection, etc.), as well as of the ash content of the coal. Pulverized-coal-fired boilers emit the highest quantity of particulate per unit of fuel because they fire the anthracite in suspension, which results in a high percentage of ash carryover into the exhaust gases. Traveling-grate stokers and hand-fired units, on the other hand, produce much less particulate per unit of fuel fired. This is because combustion takes place in a quiescent fuel bed and does not result in significant ash carryover into the exhaust gases. In general, particulate emissions from traveling-grate stokers will increase during sootblowing, flyash reinjection, and with higher underfeed air rates through the fuel bed. Higher underfeed air rates, in turn, result from higher grate loadings and the use of forced-draft fans rather than natural draft to supply combustion air. Smoking is rarely a problem because of anthracite's low volatile-matter content.

Limited data are available on the emission of gaseous pollutants from anthracite combustion. It is assumed, based on data derived from bituminous coal combustion, that a large fraction of the fuel sulfur is emitted as sulfur oxides. Moreover, because combustion equipment, excess air rates, combustion temperatures, etc., are similar between anthracite and bituminous coal combustion, nitrogen oxide and carbon monoxide emissions are assumed to be similar, as well. On the other hand, hydrocarbon emissions are expected to be considerably lower because the volatile-matter content of anthracite is significantly less than that of bituminous coal.

Air pollution control of emissions from anthracite combustion has mainly been limited to particulate matter. The most efficient particulate controls--fabric filters, scrubbers, and electrostatic precipitators--have been installed on large pulverized-anthracite-fired boilers. Fabric filters and venturi scrubbers can effect collection efficiencies exceeding 99 percent. Electrostatic precipitators, on the other hand, are typically only 90 to 97 percent efficient due to the characteristic high resistivity of the low-sulfur anthracite flyash. Higher efficiencies can reportedly be achieved using larger precipitators and flue gas conditioning. Mechanical collectors are frequently employed upstream from these devices for large-particle removal.

Traveling-grate stokers are often uncontrolled. Indeed, particulate control has often been considered unnecessary because of anthracite's low smoking tendencies and due to the fact that a significant fraction of the large-sized flyash from stokers is readily collected in flyash hoppers as well as in the breeching and base of the stack. Cyclone collectors have been employed on traveling-grate stokers;

limited information suggests these devices may be up to 75 percent efficient on particulate. Flyash reinjection, frequently employed in traveling-grate stokers to enhance fuel-use efficiency, tends to increase particulate emissions per unit of fuel combusted.

Emission factors for anthracite combustion are presented in Table 1.2-1.

Table 1.2-1. EMISSION FACTORS FOR ANTHRACITE COMBUSTION, BEFORE CONTROLS
EMISSION FACTOR RATING: B

Type of furnace	Emissions[a]									
	Particulate		Sulfur oxides[b]		Hydrocarbons[c]		Carbon monoxide[d]		Nitrogen oxides[e]	
	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT
Pulverized coal	17A[f]	8.5A[f]	38S	19S	Neg	Neg	1	0.5	18	9
Traveling grate	1A[g]	0.5A[g]	38S	19S	Neg	Neg	1	0.5	10	5
Hand-fired	10[h]	5[h]	38S	19S	2.5	1.25	90	45	3	1.5

[a] All emission factors are per unit of anthracite fired.

[b] These factors are based on the assumption that, as with bituminous coal combustion, most of the fuel sulfur is emitted as sulfur oxides. Limited data in Reference 5 verify this assumption for pulverized-anthracite-fired boilers. Generally most of these emissions are sulfur dioxide; however, approximately 1 to 3 percent are sulfur trioxide.

[c] Hydrocarbon emissions from anthracite combustion are assumed to be lower than from bituminous coal combustion because of anthracite's much lower volatile-matter content. No emissions data are available to verify this assumption.

[d] The carbon monoxide factors for pulverized-anthracite-fired boilers and hand-fired units are from Table 1.1-2.and are based on the similarity between anthracite and bituminous coal combustion. The pulverized-coal-fired boilers factor is substantiated by additional data in Reference 10. The factor for traveling-grate stokers is based on limited information in Reference 8. Carbon monoxide emissions may increase by several orders of magnitude if a boiler is not properly operated or well maintained.

[e] The nitrogen oxide factors for pulverized-anthracite-fired boilers and hand-fired units are assumed to be similar to those for bituminous coal combustion given in Table 1.1-2. The factors for traveling-grate stokers are based on Reference 8.

[f] These factors are based on the similarity between anthracite and bituminous coal combustion and on limited data in Reference 5. Note that all pulverized-anthracite-fired boilers operate in the dry tap or dry bottom mode due to anthracite's characteristically high ash-fusion temperature. The letter A on units other than hand-fired equipment indicates that the weight percentage of ash in the coal should be multiplied by the value given.

[g] Based on information in References 2,4,8, and 9. These factors account for limited fallout that may occur in fallout chambers and stack breeching. Emission factors for individual boilers may vary from 0.5A lb/ton (0.25A kg/MT) to 3A lb/ton (1.5A kg/MT), and as high as 5A lb/ton (2.5A kg/MT) during soot blowing.

[h] Based on limited information in Reference 2.

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1.3 FUEL OIL COMBUSTION

by Tom Lahre

1.3.1 General[1,2]

Fuel oils are broadly classified into two major types: distillate and residual. Distillate oils (fuel oil grades 1 and 2) are used mainly in domestic and small commercial applications in which easy fuel burning is required. Distillates are more volatile and less viscous than residual oils as well as cleaner, having negligible ash and nitrogen contents and usually containing less than 0.3 percent sulfur (by weight). Residual oils (fuel oil grades 4, 5, and 6), on the other hand, are used mainly in utility, industrial, and large commercial applications in which sophisticated combustion equipment can be utilized. (Grade 4 oil is sometimes classified as a distillate; grade 6 is sometimes referred to as Bunker C.) Being more viscous and less volatile than distillate oils, the heavier residual oils (grades 5 and 6) must be heated for ease of handling and to facilitate proper atomization. Because residual oils are produced from the residue left over after the lighter fractions (gasoline, kerosene, and distillate oils) have been removed from the crude oil, they contain significant quantities of ash, nitrogen, and sulfur. Properties of typical fuel oils are given in Appendix A.

1.3.2 Emissions

Emissions from fuel oil combustion are dependent on the grade and composition of the fuel, the type and size of the boiler, the firing and loading practices used, and the level of equipment maintenance. Table 1.3-1 presents emission factors for fuel oil combustion in units without control equipment. Note that the emission factors for industrial and commercial boilers are divided into distillate and residual oil categories because the combustion of each produces significantly different emissions of particulates, SO_x, and NO_x. The reader is urged to consult the references cited for a detailed discussion of all of the parameters that affect emissions from oil combustion.

1.3.2.1 Particulates[3-6, 12, 13] – Particulate emissions are most dependent on the grade of fuel fired. The lighter distillate oils result in significantly lower particulate formation than do the heavier residual oils. Among residual oils, grades 4 and 5 usually result in less particulate than does the heavier grade 6.

In boilers firing grade 6, particulate emissions can be described, on the average, as a function of the sulfur content of the oil. As shown in Table 1.3-1 (footnote c), particulate emissions can be reduced considerably when low-sulfur grade 6 oil is fired. This is because low-sulfur grade 6, whether refined from naturally occurring low-sulfur crude oil or desulfurized by one of several processes currently in practice, exhibits substantially lower viscosity and reduced asphaltene, ash, and sulfur content – all of which result in better atomization and cleaner combustion.

Boiler load can also affect particulate emissions in units firing grade 6 oil. At low load conditions, particulate emissions may be lowered by 30 to 40 percent from utility boilers and by as much as 60 percent from small industrial and commercial units. No significant particulate reductions have been noted at low loads from boilers firing any of the lighter grades, however. At too low a load condition, proper combustion conditions cannot be maintained and particulate emissions may increase drastically. It should be noted, in this regard, that any condition that prevents proper boiler operation can result in excessive particulate formation.

1.3.2.2 Sulfur Oxides (SO_x)[1-5] – Total sulfur oxide emissions are almost entirely dependent on the sulfur content of the fuel and are not affected by boiler size, burner design, or grade of fuel being fired. On the average, more than 95 percent of the fuel sulfur is converted to SO_2, with about 1 to 3 percent further oxidized to SO_3. Sulfur trioxide readily reacts with water vapor (both in the air and in the flue gases) to form a sulfuric acid mist.

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Table 1.3-1. EMISSION FACTORS FOR FUEL OIL COMBUSTION
EMISSION FACTOR RATING: A

Pollutant	Type of boiler[a]							
	Power plant		Industrial and commercial				Domestic	
	Residual oil		Residual oil		Distillate oil		Distillate oil	
	$lb/10^3$ gal	$kg/10^3$ liter	$lb/10^3$ gal	$kg/10^3$ liter	$lb/10^3$ gal	$kg/10^3$ liter	$lb/10^3$ gal	$kg/10^3$ liter
Particulate[b]	c	c	c	c	2	0.25	2.5	0.31
Sulfur dioxide[d]	157S	19S	157S	19S	142S	17S	142S	17S
Sulfur trioxide[d]	2S	0.25S	2S	0.25S	2S	0.25S	2S	0.25S
Carbon monoxide[e]	5	0.63	5	0.63	5	0.63	5	0.63
Hydrocarbons (total, as CH_4)[f]	1	0.12	1	0.12	1	0.12	1	0.12
Nitrogen oxides (total, as NO_2)[g]	105(50)[h,i]	12.6(6.25)[h,i]	60[j]	7.5[j]	22	2.8	18	2.3

[a] Boilers can be classified, roughly, according to their gross (higher) heat input rate, as shown below.

Power plant (utility) boilers: $>250 \times 10^6$ Btu/hr
($>63 \times 10^6$ kg-cal/hr)

Industrial boilers: $>15 \times 10^6$, but $<250 \times 10^6$ Btu/hr
($>3.7 \times 10^6$, but $<63 \times 10^6$ kg-cal/hr)

Commercial boilers: $>0.5 \times 10^6$, but $<15 \times 10^6$ Btu/hr
($>0.13 \times 10^6$, but $<3.7 \times 10^6$ kg-cal/hr)

Domestic (residential) boilers: $<0.5 \times 10^6$ Btu/hr
($<0.13 \times 10^6$ kg-cal/hr)

[b] Based on References 3 through 6. Particulate is defined in this section as that material collected by EPA Method 5 (front half catch)[7].

[c] Particulate emission factors for residual oil combustion are best described, on the average, as a function of fuel oil grade and sulfur content, as shown below.

Grade 6 oil: $lb/10^3$ gal = 10 (S) + 3
[$kg/10^3$ liter = 1.25 (S) + 0.38]
Where: S is the percentage, by weight, of sulfur in the oil

Grade 5 oil: 10 $lb/10^3$ gal (1.25 $kg/10^3$ liter)

Grade 4 oil: 7 $lb/10^3$ gal (0.88 $kg/10^3$ liter)

[d] Based on References 1 through 5. S is the percentage, by weight, of sulfur in the oil.

[e] Based on References 3 through 5 and 8 through 10. Carbon monoxide emissions may increase by a factor of 10 to 100 if a unit is improperly operated or not well maintained.

[f] Based on References 1, 3 through 5, and 10. Hydrocarbon emissions are generally negligible unless unit is improperly operated or not well maintained, in which case emissions may increase by several orders of magnitude.

[g] Based on References 1 through 5 and 8 through 11.

[h] Use 50 $lb/10^3$ gal (6.25 $kg/10^3$ liter) for tangentially fired boilers and 105 $lb/10^3$ gal (12.6 $kg/10^3$ liter) for all others, at full load, and normal (>15 percent) excess air. At reduced loads, NO_x emissions are reduced by 0.5 to 1 percent, on the average, for every percentage reduction in boiler load.

[i] Several combustion modifications can be employed for NO_x reduction: (1) limited excess air firing can reduce NO_x emissions by 5 to 30 percent, (2) staged combustion can reduce NO_x emissions by 20 to 45 percent, and (3) flue gas recirculation can reduce NO_x emissions by 10 to 45 percent. Combinations of the modifications have been employed to reduce NO_x emissions by as much as 60 percent in certain boilers. See section 1.4 for a discussion of these NO_x-reducing techniques.

[j] Nitrogen oxides emissions from residual oil combustion in industrial and commercial boilers are strongly dependent on the fuel nitrogen content and can be estimated more accurately by the following empirical relationship:

lb $NO_2/10^3$ gal = 22 + 400 $(N)^2$
[kg $NO_2/10^3$ liters = 2.75 + 50 $(N)^2$]

Where: N is the percentage, by weight, of nitrogen in the oil. Note: For residual oils having high ($>0.5\%$, by weight) nitrogen contents, one should use 120 lb $NO_2/10^3$ gal (15 kg $NO_2/10^3$ liter) as an emission factor.

1.3.2.3 Nitrogen Oxides (NO_x)[1-6, 8-11, 14] – Two mechanisms form nitrogen oxides: oxidation of fuel-bound nitrogen and thermal fixation of the nitrogen present in combustion air. Fuel NO_x are primarily a function of the nitrogen content of the fuel and the available oxygen (on the average, about 45 percent of the fuel nitrogen is converted to NO_x, but this may vary from 20 to 70 percent). Thermal NO_x, on the other hand, are largely a function of peak flame temperature and available oxygen – factors which are dependent on boiler size, firing configuration, and operating practices.

Fuel nitrogen conversion is the more important NO_x-forming mechanism in boilers firing residual oil. Except in certain large units having unusually high peak flame temperatures, or in units firing a low-nitrogen residual oil, fuel NO_x will generally account for over 50 percent of the total NO_x generated. Thermal fixation, on the other hand, is the predominant NO_x-forming mechanism in units firing distillate oils, primarily because of the negligible nitrogen content in these lighter oils. Because distillate-oil-fired boilers usually have low heat release rates, however, the quantity of thermal NO_x formed in them is less than in larger units.

A number of variables influence how much NO_x is formed by these two mechanisms. One important variable is firing configuration. Nitrogen oxides emissions from tangentially (corner) fired boilers are, on the average, only half those of horizontally opposed units. Also important are the firing practices employed during boiler operation. The use of limited excess air firing, flue gas recirculation, staged combustion, or some combination thereof, may result in NO_x reductions ranging from 5 to 60 percent. (See section 1.4 for a discussion of these techniques.) Load reduction can likewise decrease NO_x production. Nitrogen oxides emissions may be reduced from 0.5 to 1 percent for each percentage reduction in load from full load operation. It should be noted that most of these variables, with the exception of excess air, are applicable only in large oil-fired boilers. Limited excess air firing is possible in many small boilers, but the resulting NO_x reductions are not nearly as significant.

1.3.2.4 Other Pollutants[1, 3-5, 8-10, 14] – As a rule, only minor amounts of hydrocarbons and carbon monoxide will be produced during fuel oil combustion. If a unit is operated improperly or not maintained, however, the resulting concentrations of these pollutants may increase by several orders of magnitude. This is most likely to be the case with small, often unattended units.

1.3.3 Controls

Various control devices and/or techniques may be employed on oil-fired boilers depending on the type of boiler and the pollutant being controlled. All such controls may be classified into three categories: boiler modification, fuel substitution, and flue gas cleaning.

1.3.3.1 Boiler Modification[1-4, 8, 9, 13, 14] – Boiler modification includes any physical change in the boiler apparatus itself or in the operation thereof. Maintenance of the burner system, for example, is important to assure proper atomization and subsequent minimization of any unburned combustibles. Periodic tuning is important in small units to maximize operating efficiency and minimize pollutant emissions, particularly smoke and CO. Combustion modifications such as limited excess air firing, flue gas recirculation, staged combustion, and reduced load operation all result in lowered NO_x emissions in large facilities. (See Table 1.3-1 for specific reductions possible through these combustion modifications.)

1.3.3.2 Fuel Substitution[3-5, 12] – Fuel substitution, that is, the firing of "cleaner" fuel oils, can substantially reduce emissions of a number of pollutants. Lower sulfur oils, for instance, will reduce SO_x emissions in all boilers regardless of size or type of unit or grade of oil fired. Particulates will generally be reduced when a better grade of oil is fired. Nitrogen oxide emissions will be reduced by switching to either a distillate oil or a residual oil containing less nitrogen. The practice of fuel substitution, however, may be limited by the ability of a given operation to fire a better grade of oil as well as the cost and availability thereof.

1.3.3.3 Flue Gas Cleaning[6, 15-21] – Flue gas cleaning equipment is generally only employed on large oil-fired boilers. Mechanical collectors, a prevalent type of control device, are primarily useful in controlling particulates generated during soot blowing, during upset conditions, or when a very dirty, heavy oil is fired. During these situations, high efficiency cyclonic collectors can effect up to 85 percent control of particulate. Under normal firing conditions, however, or when a clean oil is combusted, cyclonic collectors will not be nearly as effective.

Electrostatic precipitators are commonly found in power plants that at one time fired coal. Precipitators that were designed for coal flyash provide only 40 to 60 percent control of oil-fired particulate. Collection efficiencies of up to 90 percent, however, have been reported for new or rebuilt devices that were specifically designed for oil-firing units.

Scrubbing systems have been installed on oil-fired boilers, especially of late, to control both sulfur oxides and particulate. These systems can achieve SO_2 removal efficiencies of up to 90 to 95 percent and provide particulate control efficiencies on the order of 50 to 60 percent. The reader should consult References 20 and 21 for details on the numerous types of flue gas desulfurization systems currently available or under development.

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1.4 NATURAL GAS COMBUSTION

Revised by Thomas Lahre

1.4.1 General [1,2]

Natural gas has become one of the major fuels used throughout the country. It is used mainly for power generation, for industrial process steam and heat production, and for domestic and commercial space heating. The primary component of natural gas is methane, although varying amounts of ethane and smaller amounts of nitrogen, helium, and carbon dioxide are also present. The average gross heating value of natural gas is approximately 1050 Btu/stdft^3 (9350 kcal/$\underline{N}$m^3), varying generally between 1000 and 1100 Btu/stdft^3 (8900 to 9800 kcal/$\underline{N}$m^3).

Because natural gas in its original state is a gaseous, homogenous fluid, its combustion is simple and can be precisely controlled. Common excess air rates range from 10 to 15 percent; however, some large units operate at excess air rates as low as 5 percent to maximize efficiency and minimize nitrogen oxide (NO_x) emissions.

1.4.2 Emissions and Controls [3-16]

Even though natural gas is considered to be a relatively clean fuel, some emissions can occur from the combustion reaction. For example, improper operating conditions, including poor mixing, insufficient air, etc., may cause large amounts of smoke, carbon monoxide, and hydrocarbons to be produced. Moreover, because a sulfur-containing mercaptan is added to natural gas for detection purposes, small amounts of sulfur oxides will also be produced in the combustion process.

Nitrogen oxides are the major pollutants of concern when burning natural gas. Nitrogen oxide emissions are a function of the temperature in the combustion chamber and the rate of cooling of the combustion products. Emission levels generally vary considerably with the type and size of unit and are also a function of loading.

In some large boilers, several operating modifications have been employed for NO_x control. Staged combustion, for example, including off-stoichiometric firing and/or two-stage combustion, can reduce NO_x emissions by 30 to 70 percent. In off-stoichiometric firing, also called "biased firing," some burners are operated fuel-rich, some fuel-lean, while others may supply air only. In two-staged combustion, the burners are operated fuel-rich (by introducing only 80 to 95 percent stoichiometric air) with combustion being completed by air injected above the flame zone through second-stage "NO-ports." In staged combustion, NO_x emissions are reduced because the bulk of combustion occurs under fuel-rich, reducing conditions.

Other NO_x-reducing modifications include low excess air firing and flue gas recirculation. In low excess air firing, excess air levels are kept as low as possible without producing unacceptable levels of unburned combustibles (carbon monoxide, hydrocarbons, and smoke) and/or other operational problems. This technique can reduce NO_x emissions by 10 to 30 percent primarily because of the lack of availability of oxygen during combustion. Flue gas recirculation into the primary combustion zone, because the flue gas is relatively cool and oxygen deficient, can also lower NO_x emissions by 20 to 60 percent depending on the amount of gas recirculated. At present only a few systems have this capability, however.

Combinations of the above combustion modifications may also be employed to further reduce NO_x emissions. In some boilers, for instance, NO_x reductions as high as 70 to 90 percent have been produced as a result of employing several of these techniques simultaneously. In general, however, because the net effect of any of these combinations varies greatly, it is difficult to predict what the overall reductions will be in any given unit.

Emission factors for natural gas combustion are presented in Table 1.4-1. Flue gas cleaning equipment has not been utilized to control emissions from natural gas combustion equipment.

Table 1.4-1. EMISSION FACTORS FOR NATURAL-GAS COMBUSTION
EMISSION FACTOR RATING: A

Pollutant	Type of unit					
	Power plant		Industrial process boiler		Domestic and commercial heating	
	lb/10^6 ft^3	kg/10^6 m^3	lb/10^6 ft^3	kg/10^6 m^3	lb/10^6 ft^3	kg/10^6 m^3
Particulates[a]	5-15	80-240	5-15	80-240	5-15	80-240
Sulfur oxides (SO_2)[b]	0.6	9.6	0.6	9.6	0.6	9.6
Carbon monoxide[c]	17	272	17	272	20	320
Hydrocarbons (as CH_4)[d]	1	16	3	48	8	128
Nitrogen oxides (NO_2)[e]	700[f-h]	11,200[f-h]	(120-230)[i]	(1920-3680)[i]	(80-120)[j]	(1280-1920)[j]

[a] References 4,7,8,12.

[b] Reference 4 (based on an average sulfur content of natural gas of 2000 gr/10^6 stdft^3 (4600 g/10^6 $\underline{N}m^3$).

[c] References 5, 8-12.

[d] References 8, 9, 12.

[e] References 3-9, 12-16.

[f] Use 300 lb/10^6 stdft^3 (4800 kg/10^6 $\underline{N}m^3$) for tangentially fired units.

[g] At reduced loads, multiply this factor by the load reduction coefficient given in Figure 1.4-1.

[h] See text for potential NO_x reductions due to combustion modifications. Note that the NO_x reduction from these modifications will also occur at reduced load conditions.

[i] This represents a typical range for many industrial boilers. For large industrial units (> 100 MMBtu/hr) use the NO_x factors presented for power plants.

[j] Use 80 (1280) for domestic heating units and 120 (1920) for commercial units.

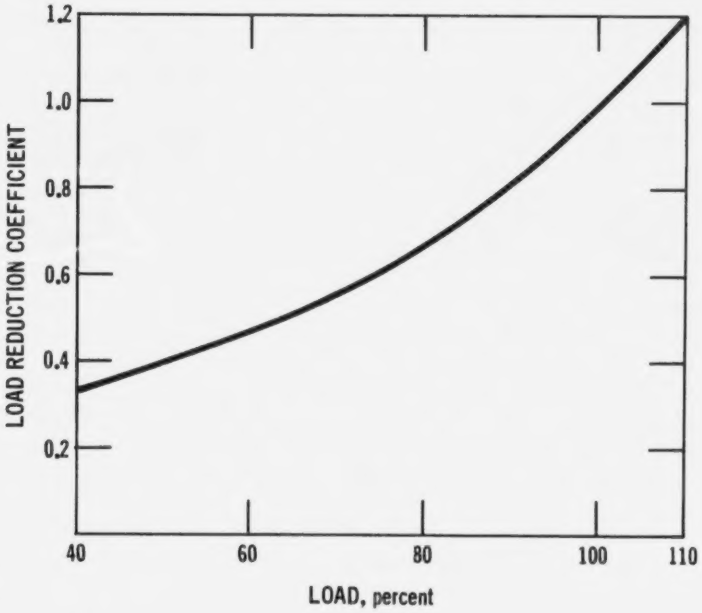

Figure 1.4-1. Load reduction coefficient as function of boiler load. (Used to determine NO_x reductions at reduced loads in large boilers.)

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1.5 LIQUEFIED PETROLEUM GAS COMBUSTION

Revised by Thomas Lahre

1.5.1 General[1]

Liquefied petroleum gas, commonly referred to as LPG, consists mainly of butane, propane, or a mixture of the two, and of trace amounts of propylene and butylene. This gas, obtained from oil or gas wells as a by-product of gasoline refining, is sold as a liquid in metal cylinders under pressure and, therefore, is often called bottled gas. LPG is graded according to maximum vapor pressure with Grade A being predominantly butane, Grade F being predominantly propane, and Grades B through E consisting of varying mixtures of butane and propane. The heating value of LPG ranges from 97,400 Btu/gallon (6,480 kcal/liter) for Grade A to 90,500 Btu/gallon (6,030 kcal/liter) for Grade F. The largest market for LPG is the domestic-commercial market, followed by the chemical industry and the internal combustion engine.

1.5.2 Emissions[1]

LPG is considered a "clean" fuel because it does not produce visible emissions. Gaseous pollutants such as carbon monoxide, hydrocarbons, and nitrogen oxides do occur, however. The most significant factors affecting these emissions are the burner design, adjustment, and venting.[2] Improper design, blocking and clogging of the flue vent, and lack of combustion air result in improper combustion that causes the emission of aldehydes, carbon monoxide, hydrocarbons, and other organics. Nitrogen oxide emissions are a function of a number of variables including temperature, excess air, and residence time in the combustion zone. The amount of sulfur dioxide emitted is directly proportional to the amount of sulfur in the fuel. Emission factors for LPG combustion are presented in Table 1.5-1.

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Table 1.5-1. EMISSION FACTORS FOR LPG COMBUSTION[a]
EMISSION FACTOR RATING: C

Pollutant	Industrial process furnaces				Domestic and commercial furnaces			
	Butane		Propane		Butane		Propane	
	lb/10^3 gal	kg/10^3 liters	lb/10^3 gal	kg/10^3 liters	lb/10^3 gal	kg/10^3 liters	lb/10^3 gal	kg/10^3 liters
Particulates	1.8	0.22	1.7	0.20	1.9	0.23	1.8	0.22
Sulfur oxides[b]	0.09S	0.01S	0.09S	0.01S	0.09S	0.01S	0.09S	0.01S
Carbon monoxide	1.6	0.19	1.5	0.18	2.0	0.24	1.9	0.23
Hydrocarbons	0.3	0.036	0.3	0.036	0.8	0.096	0.7	0.084
Nitrogen oxides[c]	12.1	1.45	11.2	1.35	(8 to 12)[d]	(1.0 to 1.5)[d]	(7 to 11)[d]	(0.8 to 1.3)[d]

[a] LPG emission factors calculated assuming emissions (excluding sulfur oxides) are the same, on a heat input basis, as for natural gas combustion.

[b] S equals sulfur content expressed in grains per 100 ft^3 gas vapor; e.g., if the sulfur content is 0.16 grain per 100 ft^3 (0.366 g/100 m^3) vapor, the SO_2 emission factor would be 0.09 x 0.16 or 0.014 lb SO_2 per 1000 gallons (0.01 x 0.366 or 0.0018 kg $SO_2/10^3$ liters) butane burned.

[c] Expressed as NO_2.

[d] Use lower value for domestic units and higher value for commercial units.

1.6 WOOD/BARK WASTE COMBUSTION IN BOILERS

Revised by Thomas Lahre

1.6.1 General [1-3]

Today, the burning of wood/bark waste in boilers is largely confined to those industries where it is available as a by-product. It is burned both to recover heat energy and to alleviate a potential solid waste disposal problem. Wood/bark waste may include large pieces such as slabs, logs, and bark strips as well as smaller pieces such as ends, shavings, and sawdust. Heating values for this waste range from 8000 to 9000 Btu/lb, on a dry basis; however, because of typical moisture contents of 40 to 75 percent, the as-fired heating values for many wood/bark waste materials range as low as 4000 to 6000 Btu/lb. Generally, bark is the major type of waste burned in pulp mills; whereas, a variable mixture of wood and bark waste, or wood waste alone, is most frequently burned in the lumber, furniture, and plywood industries.

1.6.2 Firing Practices[1-3]

A variety of boiler firing configurations are utilized for burning wood/bark waste. One common type in smaller operations is the Dutch Oven, or extension type of furnace with a flat grate. In this unit the fuel is fed through the furnace roof and burned in a cone-shaped pile on the grate. In many other, generally larger, operations, more conventional boilers have been modified to burn wood/bark waste. These units may include spreader stokers with traveling grates, vibrating grate stokers, etc., as well as tangentially fired or cyclone fired boilers. Generally, an auxiliary fuel is burned in these units to maintain constant steam when the waste fuel supply fluctuates and/or to provide more steam than is possible from the waste supply alone.

1.6.3 Emissions [1,2,4-8]

The major pollutant of concern from wood/bark boilers is particulate matter although other pollutants, particularly carbon monoxide, may be emitted in significant amounts under poor operating conditions. These emissions depend on a number of variables including (1) the composition of the waste fuel burned, (2) the degree of fly-ash reinjection employed, and (3) furnace design and operating conditions.

The composition of wood/bark waste depends largely on the industry from whence it originates. Pulping operations, for instance, produce great quantities of bark that may contain more than 70 percent moisture (by weight) as well as high levels of sand and other noncombustibles. Because of this, bark boilers in pulp mills may emit considerable amounts of particulate matter to the atmosphere unless they are well controlled. On the other hand, some operations such as furniture manufacture, produce a clean, dry (5 to 50 percent moisture) wood waste that results in relatively few particulate emissions when properly burned. Still other operations, such as sawmills, burn a variable mixture of bark and wood waste that results in particulate emissions somewhere in between these two extremes.

Fly-ash reinjection, which is commonly employed in many larger boilers to improve fuel-use efficiency, has a considerable effect on particulate emissions. Because a fraction of the collected fly-ash is reinjected into the boiler, the dust loading from the furnace, and consequently from the collection device, increases significantly per ton of wood waste burned. It is reported that full reinjection can cause a 10-fold increase in the dust loadings of some systems although increases of 1.2 to 2 times are more typical for boilers employing 50 to 100 percent reinjection. A major factor affecting this dust loading increase is the extent to which the sand and other non-combustibles can be successfully separated from the fly-ash before reinjection to the furnace.

Furnace design and operating conditions are particularly important when burning wood and bark waste. For example, because of the high moisture content in this waste, a larger area of refractory surface should be provided to dry the fuel prior to combustion. In addition, sufficient secondary air must be supplied over the fuel bed to burn the volatiles that account for most of the combustible material in the waste. When proper drying conditions do not exist, or when sufficient secondary air is not available, the combustion temperature is lowered, incomplete combustion occurs, and increased particulate, carbon monoxide, and hydrocarbon emissions will result.

Emission factors for wood waste boilers are presented in Table 1.6-1. For boilers where fly-ash reinjection is employed, two factors are shown: the first represents the dust loading reaching the control equipment; the value in parenthesis represents the dust loading after controls assuming about 80 percent control efficiency. All other factors represent uncontrolled emissions.

Table 1.6-1. EMISSION FACTORS FOR WOOD AND BARK WASTE COMBUSTION IN BOILERS
EMISSION FACTOR RATING: B

Pollutant	Emissions	
	lb/ton	kg/MT
Particulates[a]		
Bark[b,c]		
With fly-ash reinjection[d]	75 (15)	37.5 (7.5)
Without fly-ash reinjection	50	25
Wood/bark mixture[b,e]		
With fly-ash reinjection[d]	45 (9)	22.5 (4.5)
Without fly-ash reinjection	30	15
Wood[f,g]	5-15	2.5-7.5
Sulfur oxides (SO_2)[h,i]	1.5	0.75
Carbon monoxide[j]	2-60	1-30
Hydrocarbons[k]	2-70	1-35
Nitrogen oxides (NO_2)[l]	10	5

[a] These emission factors were determined for boilers burning gas or oil as an auxiliary fuel, and it was assumed all particulates resulted from the waste fuel alone. When coal is burned as an auxiliary fuel, the appropriate emission factor from Table 1.1-2 should be used in addition to the above factor.

[b] These factors based on an as-fired moisture content of 50 percent.

[c] References 2, 4, 9.

[d] This factor represents a typical dust loading reaching the control equipment for boilers employing fly-ash reinjection. The value in parenthesis represents emissions after the control equipment assuming an average efficiency of 80 percent.

[e] References 7, 10.

[f] This waste includes clean, dry (5 to 50 percent moisture) sawdust, shavings, ends, etc., and no bark. For well designed and operated boilers use lower value and higher values for others. This factor is expressed on an as-fired moisture content basis assuming no fly-ash reinjection.

[g] References 11-13.

[h] This factor is calculated by material balance assuming a maximum sulfur content of 0.1 percent in the waste. When auxiliary fuels are burned, the appropriate factors from Tables 1.1-2, 1.3-1, or 1.4-1 should be used in addition to determine sulfur oxide emissions.

[i] References 1, 5, 7.

[j] This factor is based on engineering judgment and limited data from references 11 through 13. Use lower values for well designed and operated boilers.

[k] This factor is based on limited data from references 13 through 15. Use lower values for well designed and operated boilers.

[l] Reference 16.

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1.7 LIGNITE COMBUSTION

by Thomas Lahre

1.7.1 General[1-4]

Lignite is a geologically young coal whose properties are intermediate to those of bituminous coal and peat. It has a high moisture content (35 to 40 percent, by weight) and a low heating value (6000 to 7500 Btu/lb, wet basis) and is generally only burned close to where it is mined, that is, in the midwestern States centered about North Dakota and in Texas. Although a small amount is used in industrial and domestic situations, lignite is mainly used for steam-electric production in power plants. In the past, lignite was mainly burned in small stokers; today the trend is toward use in much larger pulverized-coal-fired or cyclone-fired boilers.

The major advantage to firing lignite is that, in certain geographical areas, it is plentiful, relatively low in cost, and low in sulfur content (0.4 to 1 percent by weight, wet basis). Disadvantages are that more fuel and larger facilities are necessary to generate each megawatt of power than is the case with bituminous coal. There are several reasons for this. First, the higher moisture content of lignite means that more energy is lost in the gaseous products of combustion, which reduces boiler efficiency. Second, more energy is required to grind lignite to the specified size needed for combustion, especially in pulverized coal-fired units. Third, greater tube spacing and additional soot blowing are required because of the higher ash-fouling tendencies of lignite. Fourth, because of its lower heating value, more fuel must be handled to produce a given amount of power because lignite is not generally cleaned or dried prior to combustion (except for some drying that may occur in the crusher or pulverizer and during subsequent transfer to the burner). Generally, no major problems exist with the handling or combustion of lignite when its unique characteristics are taken into account.

1.7.2 Emissions and Controls[2-8]

The major pollutants of concern when firing lignite, as with any coal, are particulates, sulfur oxides, and nitrogen oxides. Hydrocarbon and carbon monoxide emissions are usually quite low under normal operating conditions.

Particulate emissions appear most dependent on the firing configuration in the boiler. Pulverized-coal-fired units and spreader stokers, which fire all or much of the lignite in suspension, emit the greatest quantity of flyash per unit of fuel burned. Both cyclones, which collect much of the ash as molten slag in the furnace itself, and stokers (other than spreader stokers), which retain a large fraction of the ash in the fuel bed, emit less particulate matter. In general, the higher sodium content of lignite, relative to other coals, lowers particulate emissions by causing much of the resulting flyash to deposit on the boiler tubes. This is especially the case in pulverized-coal-fired units wherein a high fraction of the ash is suspended in the combustion gases and can readily come into contact with the boiler surfaces.

Nitrogen oxides emissions are mainly a function of the boiler firing configuration and excess air. Cyclones produce the highest NO_x levels, primarily because of the high heat-release rates and temperatures reached in the small furnace sections of the boiler. Pulverized-coal-fired boilers produce less NO_x than cyclones because combustion occurs over a larger volume, which results in lower peak flame temperatures. Tangentially fired boilers produce the lowest NO_x levels in this category. Stokers produce the lowest NO_x levels mainly because most existing units are much smaller than the other firing types. In most boilers, regardless of firing configuration, lower excess air during combustion results in lower NO_x emissions.

Sulfur oxide emissions are a function of the alkali (especially sodium) content of the lignite ash. Unlike most fossil fuel combustion, in which over 90 percent of the fuel sulfur is emitted as SO_2, a significant fraction of the sulfur in lignite reacts with the ash components during combustion and is retained in the boiler ash deposits and flyash. Tests have shown that less than 50 percent of the available sulfur may be emitted as SO_2 when a high-sodium lignite is burned, whereas, more than 90 percent may be emitted with low-sodium lignite. As a rough average, about 75 percent of the fuel sulfur will be emitted as SO_2, with the remainder being converted to various sulfate salts.

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Air pollution controls on lignite-fired boilers in the United States have mainly been limited to cyclone collectors, which typically achieve 60 to 75 percent collection efficiency on lignite flyash. Electrostatic precipitators, which are widely utilized in Europe on lignitic coals and can effect 99+ percent particulate control, have seen only limited application in the United States to date although their use will probably become widespread on newer units in the future.

Nitrogen oxides reduction (up to 40 percent) has been demonstrated using low excess air firing and staged combustion (see section 1.4 for a discussion of these techniques); it is not yet known, however, whether these techniques can be continuously employed on lignite combustion units without incurring operational problems. Sulfur oxides reduction (up to 50 percent) and some particulate control can be achieved through the use of high sodium lignite. This is not generally considered a desirable practice, however, because of the increased ash fouling that may result.

Emission factors for lignite combustion are presented in Table 1.7-1.

Table 1.7-1. EMISSIONS FROM LIGNITE COMBUSTION WITHOUT CONTROL EQUIPMENT[a]
EMISSION FACTOR RATING: B

Pollutant	Type of boiler							
	Pulverized-coal		Cyclone		Spreaker stoker		Other stokers	
	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT
Particulate[b]	7.0A[c]	3.5A[c]	6A	3A	7.0A[d]	3.5A[d]	3.0A	1.5A
Sulfur oxides[e]	30S	15S	30S	15S	30S	15S	30S	15S
Nitrogen oxides[f]	14(8)[g,h]	7(4)[g,h]	17	8.5	6	3	6	3
Hydrocarbons[i]	<1.0	<0.5	<1.0	<0.5	1.0	0.5	1.0	0.5
Carbon monoxide[i]	1.0	0.5	1.0	0.5	2	1	2	1

[a] All emission factors are expressed in terms of pounds of pollutant per ton (kilograms of pollutant per metric ton) of lignite burned, wet basis (35 to 40 percent moisture, by weight).

[b] A is the ash content of the lignite by weight, wet basis. Factors based on References 5 and 6.

[c] This factor is based on data for dry-bottom, pulverized-coal-fired units only. It is expected that this factor would be lower for wet-bottom units.

[d] Limited data preclude any determination of the effect of flyash reinjection. It is expected that particulate emissions would be greater when reinjection is employed.

[e] S is the sulfur content of the lignite by weight, wet basis. For a high sodium-ash lignite ($Na_2O > 8$ percent) use 17S lb/ton (8.5S kg/MT); for a low sodium-ash lignite ($Na_2O < 2$ percent), use 35S lb/ton (17.5S kg/MT). For intermediate sodium-ash lignite, or when the sodium-ash content is unknown, use 30S lb/ton (15S kg/MT)). Factors based on References 2, 5, and 6.

[f] Expressed as NO_2. Factors based on References 2, 3, 5, 7, and 9.

[g] Use 14 lb/ton (7 kg/MT) for front-wall-fired and horizontally opposed wall-fired units and 8 lb/ton (4 kg/MT) for tangentially fired units.

[h] Nitrogen oxide emissions may be reduced by 20 to 40 percent with low excess air firing and/or staged combustion in front-fired and opposed-wall-fired units and cyclones.

[i] These factors are based on the similarity of lignite combustion to bituminous coal combustion and on limited data in Reference 7.

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1.8 BAGASSE COMBUSTION IN SUGAR MILLS

by Tom Lahre

1.8.1 General[1]

Bagasse is the fibrous residue from sugar cane that has been processed in a sugar mill. (See Section 6.12 for a brief general description of sugar cane processing.) It is fired in boilers to eliminate a large solid waste disposal problem and to produce steam and electricity to meet the mill's power requirements. Bagasse represents about 30 percent of the weight of the raw sugar cane. Because of the high moisture content (usually at least 50 percent, by weight) a typical heating value of wet bagasse will range from 3000 to 4000 Btu/lb (1660 to 2220 kcal/kg). Fuel oil may be fired with bagasse when the mill's power requirements cannot be met by burning only bagasse or when bagasse is too wet to support combustion.

The United States sugar industry is located in Florida, Louisiana, Hawaii, Texas, and Puerto Rico. Except in Hawaii, where raw sugar production takes place year round, sugar mills operate seasonally, from 2 to 5 months per year.

Bagasse is commonly fired in boilers employing either a solid hearth or traveling grate. In the former, bagasse is gravity fed through chutes and forms a pile of burning fibers. The burning occurs on the surface of the pile with combustion air supplied through primary and secondary ports located in the furnace walls. This kind of boiler is common in older mills in the sugar cane industry. Newer boilers, on the other hand, may employ traveling-grate stokers. Underfire air is used to suspend the bagasse, and overfired air is supplied to complete combustion. This kind of boiler requires bagasse with a higher percentage of fines, a moisture content not over 50 percent, and more experienced operating personnel.

1.8.2 Emissions and Controls[1]

Particulate is the major pollutant of concern from bagasse boilers. Unless an auxiliary fuel is fired, few sulfur oxides will be emitted because of the low sulfur content ($<$0.1 percent, by weight) of bagasse. Some nitrogen oxides are emitted, although the quantities appear to be somewhat lower (on an equivalent heat input basis) than are emitted from conventional fossil fuel boilers.

Particulate emissions are reduced by the use of multi-cyclones and wet scrubbers. Multi-cyclones are reportedly 20 to 60 percent efficient on particulate from bagasse boilers, whereas scrubbers (either venturi or the spray impingement type) are usually 90 percent or more efficient. Other types of control equipment have been investigated but have not been found to be practical.

Emission factors for bagasse fired boilers are shown in Table 1.8-1.

Table 1.8-1. EMISSION FACTORS FOR UNCONTROLLED BAGASSE BOILERS EMISSION FACTOR RATING: C

	Emission factors			
	lb/10^3 lb steam[a]	g/kg steam[a]	lb/ton bagasse[b]	kg/MT bagasse[b]
Particulate[c]	4	4	16	8
Sulfur oxides	d	d	d	d
Nitrogen oxides[e]	0.3	0.3	1.2	0.6

[a] Emission factors are expressed in terms of the amount of steam produced, as most mills do not monitor the amount of bagasse fired. These factors should be applied only to that fraction of steam resulting from bagasse combustion. If a significant amount (>25% of total Btu input) of fuel oil is fired with the bagasse, the appropriate emission factors from Table 1.3-1 should be used to estimate the emission contributions from the fuel oil.

[b] Emissions are expressed in terms of wet bagasse, containing approximately 50 percent moisture, by weight. As a rule of thumb, about 2 pounds (2 kg) of steam are produced from 1 pound (1 kg) of wet bagasse.

[c] Multi-cyclones are reportedly 20 to 60 percent efficient on particulate from bagasse boilers. Wet scrubbers are capable of effecting 90 or more percent particulate control. Based on Reference 1.

[d] Sulfur oxide emissions from the firing of bagasse alone would be expected to be negligible as bagasse typically contains less than 0.1 percent sulfur, by weight. If fuel oil is fired with bagasse, the appropriate factors from Table 1.3-1 should be used to estimate sulfur oxide emissions.

[e] Based on Reference 1.

Reference for Section 1.8

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1.9 RESIDENTIAL FIREPLACES

by Tom Lahre

1.9.1 General[1,2]

Fireplaces are utilized mainly in homes, lodges, etc., for supplemental heating and for their aesthetic effect. Wood is most commonly burned in fireplaces; however, coal, compacted wood waste "logs," paper, and rubbish may all be burned at times. Fuel is generally added to the fire by hand on an intermittent basis.

Combustion generally takes place on a raised grate or on the floor of the fireplace. Combustion air is supplied by natural draft, and may be controlled, to some extent, by a damper located in the chimney directly above the firebox. It is common practice for dampers to be left completely open during the fire, affording little control of the amount of air drawn up the chimney.

Most fireplaces heat a room by radiation, with a significant fraction of the heat released during combustion (estimated at greater than 70 percent) lost in the exhaust gases or through the fireplace walls. In addition, as with any fuel-burning, space-heating device, some of the resulting heat energy must go toward warming the air that infiltrates into the residence to make up for the air drawn up the chimney. The net effect is that fireplaces are extremely inefficient heating devices. Indeed, in cases where combustion is poor, where the outside air is cold, or where the fire is allowed to smolder (thus drawing air into a residence without producing apreciable radiant heat energy) a net heat loss may occur in a residence due to the use of a fireplace. Fireplace efficiency may be improved by a number of devices that either reduce the excess air rate or transfer some of the heat back into the residence that is normally lost in the exhaust gases or through the fireplace walls.

1.9.2 Emissions[1,2]

The major pollutants of concern from fireplaces are unburnt combustibles–carbon monoxide and smoke. Significant quantities of these pollutants are produced because fireplaces are grossly inefficient combustion devices due to high, uncontrolled excess air rates, low combustion temperatures, and the absence of any sort of secondary combustion. The last of these is especially important when burning wood because of its typically high (80 percent, on a dry weight basis)[3] volatile matter content.

Because most wood contains negligible sulfur, very few sulfur oxides are emitted. Sulfur oxides will be produced, of course, when coal or other sulfur-bearing fuels are burned. Nitrogen oxide emissions from fireplaces are expected to be negligible because of the low combustion temperatures involved.

Emission factors for wood and coal combustion in residential fireplaces are given in Table 1.9-1.

Table 1.9-1. EMISSION FACTORS FOR RESIDENTIAL FIREPLACES
EMISSION FACTOR RATING: C

Pollutant	Wood		Coal[a]	
	lb/ton	kg/MT	lb/ton	kg/MT
Particulate	20[b]	10[b]	30[c]	15[c]
Sulfur oxides	0[d]	0[d]	36S[e]	36S[e]
Nitrogen oxides	1[f]	0.5[f]	3	1.5
Hydrocarbons	5[g]	2.5[g]	20	10
Carbon monoxide	120[h]	60[h]	90	45

[a] All coal emission factors, except particulate, are based on data in Table 1.1-2 of Section 1.1 for hand-fired units.

[b] This includes condensable particulate. Only about 30 percent of this is filterable particulate as determined by EPA Method 5 (front-half catch).[4] Based on limited data from Reference 1.

[c] This includes condensable particulate. About 50 percent of this is filterable particulate as determined by EPA Method 5 (front-half catch).[4] Based on limited data from Reference 1.

[d] Based on negligible sulfur content in most wood.[3]

[e] S is the sulfur content, on a weight percent basis, of the coal.

[f] Based on data in Table 2.3-1 in Section 2.3 for wood waste combustion in conical burners.

[g] Nonmethane volatile hydrocarbons. Based on limited data from Reference 1.

[h] Based on limited data from Reference 1.

References for Section 1.9

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2. SOLID WASTE DISPOSAL

Revised by Robert Rosensteel

As defined in the Solid Waste Disposal Act of 1965, the term "solid waste" means garbage, refuse, and other discarded solid materials, including solid-waste materials resulting from industrial, commercial, and agricultural operations, and from community activities. It includes both combustibles and noncombustibles.

Solid wastes may be classified into four general categories: urban, industrial, mineral, and agricultural. Although urban wastes represent only a relatively small part of the total solid wastes produced, this category has a large potential for air pollution since in heavily populated areas solid waste is often burned to reduce the bulk of material requiring final disposal.[1] The following discussion will be limited to the urban and industrial waste categories.

An average of 5.5 pounds (2.5 kilograms) of urban refuse and garbage is collected per capita per day in the United States.[2] This figure does not include uncollected urban and industrial wastes that are disposed of by other means. Together, uncollected urban and industrial wastes contribute at least 4.5 pounds (2.0 kilograms) per capita per day. The total gives a conservative per capita generation rate of 10 pounds (4.5 kilograms) per day of urban and industrial wastes. Approximately 50 percent of all the urban and industrial waste generated in the United States is burned, using a wide variety of combustion methods with both enclosed and open burning[3]. Atmospheric emissions, both gaseous and particulate, result from refuse disposal operations that use combustion to reduce the quantity of refuse. Emissions from these combustion processes cover a wide range because of their dependence upon the refuse burned, the method of combustion or incineration, and other factors. Because of the large number of variables involved, it is not possible, in general, to delineate when a higher or lower emission factor, or an intermediate value should be used. For this reason, an average emission factor has been presented.

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2.1 REFUSE INCINERATION

Revised by Robert Rosensteel

2.1.1 Process Description[1-4]

The most common types of incinerators consist of a refractory-lined chamber with a grate upon which refuse is burned. In some newer incinerators water-walled furnaces are used. Combustion products are formed by heating and burning of refuse on the grate. In most cases, since insufficient underfire (undergrate) air is provided to enable complete combustion, additional over-fire air is admitted above the burning waste to promote complete gas-phase combustion. In multiple-chamber incinerators, gases from the primary chamber flow to a small secondary mixing chamber where more air is admitted, and more complete oxidation occurs. As much as 300 percent excess air may be supplied in order to promote oxidation of combustibles. Auxiliary burners are sometimes installed in the mixing chamber to increase the combustion temperature. Many small-size incinerators are single-chamber units in which gases are vented from the primary combustion chamber directly into the exhaust stack. Single-chamber incinerators of this type do not meet modern air pollution codes.

2.1.2 Definitions of Incinerator Categories[1]

No exact definitions of incinerator size categories exist, but for this report the following general categories and descriptions have been selected:

1. *Municipal incinerators* – Multiple-chamber units often have capacities greater than 50 tons (45.3 MT) per day and are usually equipped with automatic charging mechanisms, temperature controls, and movable grate systems. Municipal incinerators are also usually equipped with some type of particulate control device, such as a spray chamber or electrostatic precipitator.

2. *Industrial/commercial incinerators* – The capacities of these units cover a wide range, generally between 50 and 4,000 pounds (22.7 and 1,800 kilograms) per hour. Of either single- or multiple-chamber design, these units are often manually charged and intermittently operated. Some industrial incinerators are similar to municipal incinerators in size and design. Better designed emission control systems include gas-fired afterburners or scrubbing, or both.

3. *Trench Incinerators* – A trench incinerator is designed for the combustion of wastes having relatively high heat content and low ash content. The design of the unit is simple: a U-shaped combustion chamber is formed by the sides and bottom of the pit and air is supplied from nozzles along the top of the pit. The nozzles are directed at an angle below the horizontal to provide a curtain of air across the top of the pit and to provide air for combustion in the pit. The trench incinerator is not as efficient for burning wastes as the municipal multiple-chamber unit, except where careful precautions are taken to use it for disposal of low-ash, high-heat-content refuse, and where special attention is paid to proper operation. Low construction and operating costs have resulted in the use of this incinerator to dispose of materials other than those for which it was originally designed. Emission factors for trench incinerators used to burn three such materials[7] are included in Table 2.1-1.

4. *Domestic incinerators* – This category includes incinerators marketed for residential use. Fairly simple in design, they may have single or multiple chambers and usually are equipped with an auxiliary burner to aid combustion.

Table 2.1-1. EMISSION FACTORS FOR REFUSE INCINERATORS WITHOUT CONTROLS[a]
EMISSION FACTOR RATING: A

Incinerator type	Particulates		Sulfur oxides[b]		Carbon monoxide		Hydrocarbons[c]		Nitrogen oxides[d]	
	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT
Municipal[e]										
Multiple chamber, uncontrolled	30	15	2.5	1.25	35	17.5	1.5	0.75	3	1.5
With settling chamber and water spray system[f]	14	7	2.5	1.25	35	17.5	1.5	0.75	3	1.5
Industrial/commercial										
Multiple chamber[g]	7	3.5	2.5[h]	1.25	10	5	3	1.5	3	1.5
Single chamber[i]	15	7.5	2.5[h]	1.25	20	10	15	7.5	2	1
Trench[j]										
Wood	13	6.5	0.1[k]	0.05	NA[l]	NA	NA	NA	4	2
Rubber tires	138	69	NA	NA	NA	NA	NA	NA	NA	NA
Municipal refuse	37	18.5	2.5[h]	1.25	NA	NA	NA	NA	NA	NA
Controlled air[m]	1.4	0.7	1.5	0.75	Neg	Neg	Neg	Neg	10	5
Flue-fed single chamber[n]	30	15	0.5	0.25	20	10	15	7.5	3	1.5
Flue-fed (modified)[o,p]	6	3	0.5	0.25	10	5	3	1.5	10	5
Domestic single chamber										
Without primary burner[q]	35	17.5	0.5	0.25	300	150	100	50	1	0.5
With primary burner[r]	7	3.5	0.5	0.25	Neg	Neg	2	1	2	1
Pathological[s]	8	4	Neg	Neg	Neg	Neg	Neg	Neg	3	1.5

[a] Average factors given based on EPA procedures for incinerator stack testing.

[b] Expressed as sulfur dioxide.

[c] Expressed as methane.

[d] Expressed as nitrogen dioxide.

[e] References 5 and 8 through 14.

[f] Most municipal incinerators are equipped with at least this much control: see Table 2.1-2 for appropriate efficiencies for other controls.

[g] References 3, 5, 10, 13, and 15.

[h] Based on municipal incinerator data.

[i] References 3, 5, 10, and 15.

[j] Reference 7.

[k] Based on data for wood combustion in conical burners.

[l] Not available.

[m] Reference 9.

[n] References 3, 10, 11, 13, 15, and 16.

[o] With afterburners and draft controls.

[p] References 3, 11, and 15.

[q] References 5 and 10.

[r] Reference 5.

[s] References 3 and 9.

5. *Flue-fed incinerators* – These units, commonly found in large apartment houses, are characterized by the charging method of dropping refuse down the incinerator flue and into the combustion chamber. Modified flue-fed incinerators utilize afterburners and draft controls to improve combustion efficiency and reduce emissions.

6. *Pathological incinerators* – These are incinerators used to dispose of animal remains and other organic material of high moisture content. Generally, these units are in a size range of 50 to 100 pounds (22.7 to 45.4 kilograms) per hour. Wastes are burned on a hearth in the combustion chamber. The units are equipped with combustion controls and afterburners to ensure good combustion and minimal emissions.

7. *Controlled air incinerators* – These units operate on a controlled combustion principle in which the waste is burned in the absence of sufficient oxygen for complete combustion in the main chamber. This process generates a highly combustible gas mixture that is then burned with excess air in a secondary chamber, resulting in efficient combustion. These units are usually equipped with automatic charging mechanisms and are characterized by the high effluent temperatures reached at the exit of the incinerators.

2.1.3 Emissions and Controls[1]

Operating conditions, refuse composition, and basic incinerator design have a pronounced effect on emissions. The manner in which air is supplied to the combustion chamber or chambers has, among all the parameters, the greatest effect on the quantity of particulate emissions. Air may be introduced from beneath the chamber, from the side, or from the top of the combustion area. As underfire air is increased, an increase in fly-ash emissions occurs. Erratic refuse charging causes a disruption of the combustion bed and a subsequent release of large quantities of particulates. Large quantities of uncombusted particulate matter and carbon monoxide are also emitted for an extended period after charging of batch-fed units because of interruptions in the combustion process. In continuously fed units, furnace particulate emissions are strongly dependent upon grate type. The use of rotary kiln and reciprocating grates results in higher particulate emissions than the use of rocking or traveling grates.[14] Emissions of oxides of sulfur are dependent on the sulfur content of the refuse. Carbon monoxide and unburned hydrocarbon emissions may be significant and are caused by poor combustion resulting from improper incinerator design or operating conditions. Nitrogen oxide emissions increase with an increase in the temperature of the combustion zone, an increase in the residence time in the combustion zone before quenching, and an increase in the excess air rates to the point where dilution cooling overcomes the effect of increased oxygen concentration.[14]

Table 2.1-2 lists the relative collection efficiencies of particulate control equipment used for municipal incinerators. This control equipment has little effect on gaseous emissions. Table 2.1-1 summarizes the uncontrolled emission factors for the various types of incinerators previously discussed.

Table 2.1-2. COLLECTION EFFICIENCIES FOR VARIOUS TYPES OF MUNICIPAL INCINERATION PARTICULATE CONTROL SYSTEMS[a]

Type of system	Efficiency, %
Settling chamber	0 to 30
Settling chamber and water spray	30 to 60
Wetted baffles	60
Mechanical collector	30 to 80
Scrubber	80 to 95
Electrostatic precipitator	90 to 96
Fabric filter	97 to 99

[a] References 3, 5, 6, and 17 through 21.

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2.2 AUTOMOBILE BODY INCINERATION

Revised by Robert Rosensteel

2.2.1 Process Description

Auto incinerators consist of a single primary combustion chamber in which one or several partially stripped cars are burned. (Tires are removed.) Approximately 30 to 40 minutes is required to burn two bodies simultaneously.[2] As many as 50 cars per day can be burned in this batch-type operation, depending on the capacity of the incinerator. Continuous operations in which cars are placed on a conveyor belt and passed through a tunnel-type incinerator have capacities of more than 50 cars per 8-hour day.

2.2.2 Emissions and Controls[1]

Both the degree of combustion as determined by the incinerator design and the amount of combustible material left on the car greatly affect emissions. Temperatures on the order of 1200°F (650°C) are reached during auto body incineration.[2] This relatively low combustion temperature is a result of the large incinerator volume needed to contain the bodies as compared with the small quantity of combustible material. The use of overfire air jets in the primary combustion chamber increases combustion efficiency by providing air and increased turbulence.

In an attempt to reduce the various air pollutants produced by this method of burning, some auto incinerators are equipped with emission control devices. Afterburners and low-voltage electrostatic precipitators have been used to reduce particulate emissions; the former also reduces some of the gaseous emissions.[3,4] When afterburners are used to control emissions, the temperature in the secondary combustion chamber should be at least 1500°F (815°C). Lower temperatures result in higher emissions. Emission factors for auto body incinerators are presented in Table 2.2-1.

Table 2.2-1. EMISSION FACTORS FOR AUTO BODY INCINERATION[a]
EMISSION FACTOR RATING: B

Pollutants	Uncontrolled		With afterburner	
	lb/car	kg/car	lb/car	kg/car
Particulates[b]	2	0.9	1.5	0.68
Carbon monoxide[c]	2.5	1.1	Neg	Neg
Hydrocarbons (CH_4)[c]	0.5	0.23	Neg	Neg
Nitrogen oxides (NO_2)[d]	0.1	0.05	0.02	0.01
Aldehydes (HCOH)[d]	0.2	0.09	0.06	0.03
Organic acids (acetic)[d]	0.21	0.10	0.07	0.03

[a] Based on 250 lb (113 kg) of combustible material on stripped car body.
[b] References 2 and 4.
[c] Based on data for open burning and References 2 and 5.
[d] Reference 3.

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2.3 CONICAL BURNERS

2.3.1 Process Description[1]

Conical burners are generally a truncated metal cone with a screened top vent. The charge is placed on a raised grate by either conveyor or bulldozer; however, the use of a conveyor results in more efficient burning. No supplemental fuel is used, but combustion air is often supplemented by underfire air blown into the chamber below the grate and by overfire air introduced through peripheral openings in the shell.

2.3.2 Emissions and Controls

The quantities and types of pollutants released from conical burners are dependent on the composition and moisture content of the charged material, control of combustion air, type of charging system used, and the condition in which the incinerator is maintained. The most critical of these factors seems to be the level of maintenance on the incinerators. It is not uncommon for conical burners to have missing doors and numerous holes in the shell, resulting in excessive combustion air, low temperatures, and, therefore, high emission rates of combustible pollutants.[2]

Particulate control systems have been adapted to conical burners with some success. These control systems include water curtains (wet caps) and water scrubbers. Emission factors for conical burners are shown in Table 2.3-1.

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Table 2.3-1. EMISSION FACTORS FOR WASTE INCINERATION IN CONICAL BURNERS WITHOUT CONTROLS[a]
EMISSION FACTOR RATING: B

Type of waste	Particulates		Sulfur oxides		Carbon monoxide		Hydrocarbons		Nitrogen oxides	
	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT
Municipal refuse[b]	20(10 to 60)[c,d]	10	2	1	60	30	20	10	5	2.5
Wood refuse[e]	1[f] 7[g] 20[h]	0.5 3.5 10	0.1	0.05	130	65	11	5.5	1	0.5

[a] Moisture content as fired is approximately 50 percent for wood waste.

[b] Except for particulates, factors are based on comparison with other waste disposal practices.

[c] Use high side of range for intermittent operations charged with a bulldozer.

[d] Based on Reference 3.

[e] References 4 through 9.

[f] Satisfactory operation: properly maintained burner with adjustable underfire air supply and adjustable, tangential overfire air inlets, approximately 500 percent excess air and 700°F (370°C) exit gas temperature.

[g] Unsatisfactory operation: properly maintained burner with radial overfire air supply near bottom of shell, approximately 1200 percent excess air and 400°F (204°C) exit gas temperature.

[h] Very unsatisfactory operation: improperly maintained burner with radial overfire air supply near bottom of shell and many gaping holes in shell, approximately 1500 percent excess air and 400°F (204°C) exit gas temperature.

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2.4 OPEN BURNING

revised by Tom Lahre
and Pam Canova

2.4.1 General[1]

Open burning can be done in open drums or baskets, in fields and yards, and in large open dumps or pits. Materials commonly disposed of in this manner are municipal waste, auto body components, landscape refuse, agricultural field refuse, wood refuse, bulky industrial refuse, and leaves.

2.4.2 Emissions[1-19]

Ground-level open burning is affected by many variables including wind, ambient temperature, composition and moisture content of the debris burned, and compactness of the pile. In general, the relatively low temperatures associated with open burning increase the emission of particulates, carbon monoxide, and hydrocarbons and suppress the emission of nitrogen oxides. Sulfur oxide emissions are a direct function of the sulfur content of the refuse. Emission factors are presented in Table 2.4-1 for the open burning of municipal refuse and automobile components.

Table 2.4-1. EMISSION FACTORS FOR OPEN BURNING OF NONAGRICULTURAL MATERIAL
EMISSION FACTOR RATING: B

	Particulates	Sulfur oxides	Carbon monoxide	Hydrocarbons (CH_4)	Nitrogen oxides
Municipal refuse[a]					
lb/ton	16	1	85	30	6
kg/MT	8	0.5	42	15	3
Automobile components[b,c]					
lb/ton	100	Neg.	125	30	4
kg/MT	50	Neg.	62	15	2

[a] References 2 through 6.
[b] Upholstery, belts, hoses, and tires burned in common.
[c] Reference 2.

Emissions from agricultural refuse burning are dependent mainly on the moisture content of the refuse and, in the case of the field crops, on whether the refuse is burned in a headfire or a backfire. (Headfires are started at the upwind side of a field and allowed to progress in the direction of the wind, whereas backfires are started at the downwind edge and forced to progress in a direction opposing the wind.) Other variables such as fuel loading (how much refuse material is burned per unit of land area) and how the refuse is arranged (that is, in piles, rows, or spread out) are also important in certain instances. Emission factors for open agricultural burning are presented in Table 2.4-2 as a function of refuse type and also, in certin instances, as a function of burning techniques and/or moisture content when these variables are known to significantly affect emissions. Table 2.4-2 also presents typical fuel loading values associated with each type of refuse. These values can be used, along with the corresponding emission factors, to estimate emissions from certain categories of agricultural burning when the specific fuel loadings for a given area are not known.

Emissions from leaf burning are dependent upon the moisture content, density, and ignition location of the leaf piles. Increasing the moisture content of the leaves generally increases the amount of carbon monoxide, hydrocarbon, and particulate emissions. Increasing the density of the piles increases the amount of hydrocarbon and particulate emissions, but has a variable effect on carbon

Table 2.4-2. EMISSION FACTORS AND FUEL LOADING FACTORS FOR OPEN BURNING OF AGRICULTURAL MATERIALS[a]
EMISSION FACTOR RATING: B

Refuse category	Emission factors						Fuel loading factors (waste production)	
	Particulate[b]		Carbon monoxide		Hydrocarbons (as C_6H_{14})			
	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT	ton/acre	MT/hectare
Field crops[c]								
Unspecified	21	11	117	58	23	12	2.0	4.5
Burning technique not significant[d]								
Asparagus[e]	40	20	150	75	85	42	1.5	3.4
Barley	22	11	157	78	19	10	1.7	3.8
Corn	14	7	108	54	16	8	4.2	9.4
Cotton	8	4	176	88	6	3	1.7	3.8
Grasses	16	8	101	50	19	10		
Pineapple[f]	8	4	112	56	8	4		
Rice[g]	9	4	83	41	10	5	3.0	6.7
Safflower	18	9	144	72	26	13	1.3	2.9
Sorghum	18	9	77	38	9	4	2.9	6.5
Sugar cane[h]	7	4	71	35	10	5	11.0	24.0
Headfire burning[i]								
Alfalfa	45	23	106	53	36	18	0.8	1.8
Bean (red)	43	22	186	93	46	23	2.5	5.6
Hay (wild)	32	16	139	70	22	11	1.0	2.2
Oats	44	22	137	68	33	16	1.6	3.6
Pea	31	16	147	74	38	19	2.5	5.6
Wheat	22	11	128	64	17	9	1.9	4.3
Backfire burning[j]								
Alfalfa	29	14	119	60	37	18	0.8	1.8
Bean (red), pea	14	7	148	72	25	12	2.5	5.6
Hay (wild)	17	8	150	75	17	8	1.0	2.2
Oats	21	11	136	68	18	9	1.6	3.6
Wheat	13	6	108	54	11	6	1.9	4.3
Vine crops	5	3	51	26	7	4	2.5	5.6
Weeds								
Unspecified	15	8	85	42	12	6	3.2	7.2
Russian thistle (tumbleweed)	22	11	309	154	2	1	0.1	0.2
Tules (wild reeds)	5	3	34	17	27	14		
Orchard crops[c,k,l]								
Unspecified	6	3	52	26	10	5	1.6	3.6
Almond	6	3	46	23	8	4	1.6	3.6
Apple	4	2	42	21	4	2	2.3	5.2
Apricot	6	3	49	24	8	4	1.8	4.0
Avocado	21	10	116	58	32	16	1.5	3.4
Cherry	8	4	44	22	10	5	1.0	2.2
Citrus (orange, lemon)	6	3	81	40	12	6	1.0	2.2
Date palm	10	5	56	28	7	4	1.0	2.2
Fig	7	4	57	28	10	5	2.2	4.9

Table 2.4-2 (continued). EMISSION FACTORS AND FUEL LOADING FACTORS FOR OPEN BURNING OF AGRICULTURAL MATERIALS[a]
EMISSION FACTOR RATING: B

	Emission factors						Fuel loading factors (waste production)	
	Particulate[b]		Carbon monoxide		Hydrocarbons (as C_6H_{14})			
Refuse category	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT	ton/acre	MT/hectare
Orchard crops[c,k,l] (continued)								
Nectarine	4	2	33	16	4	2	2.0	4.5
Olive	12	6	114	57	18	9	1.2	2.7
Peach	6	3	42	21	5	2	2.5	5.6
Pear	9	4	57	28	9	4	2.6	5.8
Prune	3	2	42	21	3	2	1.2	2.7
Walnut	6	3	47	24	8	4	1.2	2.7
Forest residues								
Unspecified[m]	17	8	140	70	24	12	70	157
Hemlock, Douglas fir, cedar[n]	4	2	90	45	5	2		
Ponderosa pine[o]	12	6	195	98	14	7		

[a] Factors expressed as weight of pollutant emitted per weight of refuse material burned.

[b] Particulate matter from most agricultural refuse burning has been found to be in the submicrometer size range.[12]

[c] References 12 and 13 for emission factors; Reference 14 for fuel loading factors.

[d] For these refuse materials, no significant difference exists between emissions resulting from headfiring or backfiring.

[e] These factors represent emissions under typical high moisture conditions. If ferns are dried to less than 15 percent moisture, particulate emissions will be reduced by 30 percent, CO emission by 23 percent, and HC by 74 percent.

[f] When pineapple is allowed to dry to less than 20 percent moisture, as it usually is, the firing technique is not important. When headfired above 20 percent moisture, particulate emission will increase to 23 lb/ton (11.5 kg/MT) and HC will increase to 12 lb/ton (6 kg/MT). See Reference 11.

[g] This factor is for dry (<15 percent moisture) rice straw. If rice straw is burned at higher moisture levels, particulate emission will increase to 29 lb/ton (14.5 kg/MT), CO emission to 161 lb/ton (80.5 kg/MT), and HC emission to 21 lb/ton (10.5 kg/MT).

[h] See Section 6.12 for discussion of sugar cane burning.

[i] See accompanying text for definition of headfiring.

[j] See accompanying text for definition of backfiring. This category, for emission estimation purposes, includes another technique used occasionally for limiting emissions, called into-the-wind striplighting, which involves lighting fields in strips into the wind at 100-200 m (300-600 ft) intervals.

[k] Orchard prunings are usually burned in piles. No significant difference in emission results from burning a "cold pile" as opposed to using a roll-on technique, where prunings are bulldozed onto a bed of embers from a preceding fire.

[l] If orchard removal is the purpose of a burn, 30 ton/acre (66 MT/hectare) of waste will be produced.

[m] Reference 10. Nitrogen oxide emissions estimated at 4 lb/ton (2 kg/MT).

[n] Reference 15.

[o] Reference 16.

monoxide emissions. Arranging the leaves in conical piles and igniting around the periphery of the bottom proves to be the least desirable method of burning. Igniting a single spot on the top of the pile decreases the hydrocarbon and particulate emissions. Carbon monoxide emissions with top ignition decrease if moisture content is high but increase if moisture content is low. Particulate, hydrocarbon, and carbon monoxide emissions from windrow ignition (piling the leaves into a long row and igniting one end, allowing it to burn toward the other end) are intermediate between top and bottom ignition. Emission factors for leaf burning are presented in Table 2.4-3.

For more detailed information on this subject, the reader should consult the references cited at the end of this section.

Table 2.4-3. EMISSION FACTORS FOR LEAF BURNING[18,19]
EMISSION FACTOR RATING: B

Leaf species	Particulate[a,b]		Carbon monoxide[a]		Hydrocarbons[a,c]	
	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT
Black Ash	36	18	127	63.5	41	20.5
Modesto Ash	32	16	163	81.5	25	12.5
White Ash	43	21.5	113	57	21	10.5
Catalpa	17	8.5	89	44.5	15	7.5
Horse Chestnut	54	27	147	73.5	39	19.5
Cottonwood	38	19	90	45	32	16
American Elm	26	13	119	59.5	29	14.5
Eucalyptus	36	18	90	45	26	13
Sweet Gum	33	16.5	140	70	27	13.5
Black Locust	70	35	130	65	62	31
Magnolia	13	6.5	55	27.5	10	5
Silver Maple	66	33	102	51	25	12.5
American Sycamore	15	7.5	115	57.5	8	4
California Sycamore	10	5	104	52	5	2.5
Tulip	20	10	77	38.5	16	8
Red Oak	92	46	137	68.5	34	17
Sugar Maple	53	26.5	108	54	27	13.5
Unspecified	38	19	112	56	26	13

[a] These factors are an arithmetic average of the results obtained by burning high- and low-moisture content conical piles ignited either at the top or around the periphery of the bottom. The windrow arrangement was only tested on Modesto Ash, Catalpa, American Elm, Sweet Gum, Silver Maple, and Tulip, and the results are included in the averages for these species.

[b] The majority of particulates are submicron in size.

[c] Tests indicate hydrocarbons consist, on the average, of 42% olefins, 32% methane, 8% acetylene, and 13% other saturates.

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2.5 SEWAGE SLUDGE INCINERATION

By Thomas Lahre

2.5.1 Process Description [1-3]

Incineration is becoming an important means of disposal for the increasing amounts of sludge being produced in sewage treatment plants. Incineration has the advantages of both destroying the organic matter present in sludge, leaving only an odorless, sterile ash, as well as reducing the solid mass by about 90 percent. Disadvantages include the remaining, but reduced, waste disposal problem and the potential for air pollution. Sludge incineration systems usually include a sludge pretreatment stage to thicken and dewater the incoming sludge, an incinerator, and some type of air pollution control equipment (commonly wet scrubbers).

The most prevalent types of incinerators are multiple hearth and fluidized bed units. In multiple hearth units the sludge enters the top of the furnace where it is first dried by contact with the hot, rising, combustion gases, and then burned as it moves slowly down through the lower hearths. At the bottom hearth any residual ash is then removed. In fluidized bed reactors, the combustion takes place in a hot, suspended bed of sand with much of the ash residue being swept out with the flue gas. Temperatures in a multiple hearth furnace are 600°F (320°C) in the lower, ash cooling hearth; 1400 to 2000°F (760 to 1100°C) in the central combustion hearths, and 1000 to 1200°F (540 to 650°C) in the upper, drying hearths. Temperatures in a fluidized bed reactor are fairly uniform, from 1250 to 1500°F (680 to 820°C). In both types of furnace an auxiliary fuel may be required either during startup or when the moisture content of the sludge is too high to support combustion.

2.5.2 Emissions and Controls [1,2,4-7]

Because of the violent upwards movement of combustion gases with respect to the burning sludge, particulates are the major emissions problem in both multiple hearth and fluidized bed incinerators. Wet scrubbers are commonly employed for particulate control and can achieve efficiencies ranging from 95 to 99+ percent.

Although dry sludge may contain from 1 to 2 percent sulfur by weight, sulfur oxides are not emitted in significant amounts when sludge burning is compared with many other combustion processes. Similarly, nitrogen oxides, because temperatures during incineration do not exceed 1500°F (820°C) in fluidized bed reactors or 1600 to 2000°F (870 to 1100°C) in multiple hearth units, are not formed in great amounts.

Odors can be a problem in multiple hearth systems as unburned volatiles are given off in the upper, drying hearths, but are readily removed when afterburners are employed. Odors are not generally a problem in fluidized bed units as temperatures are uniformly high enough to provide complete oxidation of the volatile compounds. Odors can also emanate from the pretreatment stages unless the operations are properly enclosed.

Emission factors for sludge incinerators are shown in Table 2.5-1. It should be noted that most sludge incinerators operating today employ some type of scrubber.

Table 2.5-1. EMISSION FACTORS FOR SEWAGE SLUDGE INCINERATORS
EMISSION FACTOR RATING: B

Pollutant	Emissions[a]			
	Uncontrolled[b]		After scrubber	
	lb/ton	kg/MT	lb/ton	kg/MT
Particulate[c]	100	50	3	1.5
Sulfur dioxide[d]	1	0.5	0.8	0.4
Carbon monoxide[e]	Neg	Neg	Neg	Neg
Nitrogen oxides[d] (as NO_2)	6	3	5	2.5
Hydrocarbons[d]	1.5	0.75	1	0.5
Hydrogen chloride gas[d]	1.5	0.75	0.3	0.15

[a] Unit weights in terms of dried sludge.

[b] Estimated from emission factors after scrubbers.

[c] References 6-9.

[d] Reference 8.

[e] References 6, 8.

References for Section 2.5

1. Calaceto, R. R. Advances in Fly Ash Removal with Gas-Scrubbing Devices. Filtration Engineering. *1*(7):12-15, March 1970.

2. Balakrishnam, S. et al. State of the Art Review on Sludge Incineration Practices. U.S. Department of the Interior, Federal Water Quality Administration, Washington, D.C. FWQA-WPC Research Series.

3. Canada's Largest Sludge Incinerators Fired Up and Running. Water and Pollution Control. *107*(1):20-21, 24, January 1969.

4. Calaceto, R. R. Sludge Incinerator Fly Ash Controlled by Cyclonic Scrubber. Public Works. *94*(2):113-114, February 1963.

5. Schuraytz, I. M. et al. Stainless Steel Use in Sludge Incinerator Gas Scrubbers. Public Works. *103*(2):55-57, February 1972.

6. Liao, P. Design Method for Fluidized Bed Sewage Sludge Incinerators. PhD. Thesis. University of Washington, Seattle, Washington, 1972.

7. Source test data supplied by the Detroit Metropolitan Water Department, Detroit, Michigan. 1973.

8. Source test data from Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, Research Triangle Park, N.C. 1972.

9. Source test data from Dorr-Oliver, Inc., Stamford, Connecticut. 1973.

3. INTERNAL COMBUSTION ENGINE SOURCES

The internal combustion engine in both mobile and stationary applications is a major source of air pollutant emissions. Internal combustion engines were responsible for approximately 73 percent of the carbon monoxide, 56 percent of the hydrocarbons, and 50 percent of the nitrogen oxides (NO_X as NO_2) emitted during 1970 in the United States.[1] These sources, however, are relatively minor contributors of total particulate and sulfur oxides emissions. In 1970, nationwide, internal combustion sources accounted for only about 2.5 percent of the total particulate and 3.4 percent of the sulfur oxides.[1]

The three major uses for internal combustion engines are: to propel highway vehicles, to propel off-highway vehicles, and to provide power from a stationary position. Associated with each of these uses are engine duty cycles that have a profound effect on the resulting air pollutant emissions from the engine. The following sections describe the many applications of internal combustion engines, the engine duty cycles, and the resulting emissions.

DEFINITIONS USED IN CHAPTER 3

Calendar year – A cycle in the Gregorian calendar of 365 or 366 days divided into 12 months beginning with January and ending with December.

Catalytic device – A piece of emission control equipment that is anticipated to be the major component used in post 1974 light-duty vehicles to meet the Federal emission standards.

Cold vehicle operation – The first 505 seconds of vehicle operation following a 4-hour engine-off period. (for catalyst vehicles a 1-hour engine-off period).

Composite emission factor (highway vehicle) – The emissions of a vehicle in gram/mi (g/km) that results from the product of the calendar year emission rate, the speed correction factor, the temperature correction factor, and the hot/cold weighting correction factor.

Crankcase emissions – Airborne substance emitted to the atmosphere from any portion of the crankcase ventilation or lubrication systems of a motor vehicle engine.

1975 Federal Test Procecure (FTP) – The Federal motor vehicle emission test as described in the *Federal Register*, Vol. 36, Number 128, July 2, 1971.

Fuel evaporative emissions – Vaporized fuel emitted into the atmosphere from the fuel system of a motor vehicle.

Heavy-duty vehicle – A motor vehicle designated primarily for transportation of property and rated at more than 8500 pounds (3856 kilograms) gross vehicle weight (GVW) or designed primarily for transportation of persons and having a capacity of more than 12 persons.

High-altitude emission factors – Substantial changes in emission factors from gasoline-powered vehicles occur as altitude increases. These changes are caused by fuel metering enrichment because of decreasing air density. No relationship between mass emissions and altitude has been developed. Tests have been conducted at near sea level and at approximately 5000 feet (1524 meters) above sea level, however. Because most major U.S. urban areas at high altitude are close to 5000 feet (1524 meters), an arbitrary value of 3500 ft (1067 m) and above is used to define high-altitude cities.

Horsepower-hours – A unit of work.

Hot/cold weighting correction factor – The ratio of pollutant exhaust emissions for a given percentage of cold operation (w) to pollutant exhaust emissions measured on the 1975 Federal Test Procedure (20 percent cold operation) at ambient temperature (t).

Light-duty truck – Any motor vehicle designated primarily for transportation of property and rated at 8500 pounds (3856 kilograms) GVW or less. Although light-duty trucks have a load carrying capability that exceeds that of passenger cars, they are typically used primarily for personal transportation as passenger car substitutes.

Light-duty vehicle (passenger car) – Any motor vehicle designated primarily for transportation of persons and having a capacity of 12 persons or less.

Modal emission model – A mathematical model that can be used to predict the warmed-up exhaust emissions for groups of light-duty vehicles over arbitrary driving sequences.

Model year – A motor vehicle manufacturer's annual production period. If a manufacturer has no annual production period, the term "model year" means a calendar year.

Model year mix – The distribution of vehicles registered by model year expressed as a fraction of the total vehicle population.

Nitrogen oxides – The sum of the nitric oxide and nitrogen dioxide contaminants in a gas sample expressed as if the nitric oxide were in the form of nitrogen dioxide. All nitrogen oxides values in this chapter are corrected for relative humidity.

Speed correction factor – The ratio of the pollutant (p) exhaust emission factor at speed "x" to the pollutant (p) exhaust emission factor as determined by the 1975 Federal Test Procedure at 19.6 miles per hour (31.6 kilometers per hour).

Temperature correction factor – The ratio of pollutant exhaust emissions measured over the 1975 Federal Test Procedure at ambient temperature (t) to pollutant exhaust emissions measured over the 1975 Federal Test Procedure at standard temperature conditions (68 to 86°F).

Reference

1. Cavender, J., D. S. Kircher, and J. R. Hammerle. Nationwide Air Pollutant Trends (1940-1970). U. S. Environmental Protection Agency, Office of Air and Water Programs. Research Triangle Park, N.C. Publication Number AP-115. April 1973.

3.1 HIGHWAY VEHICLES

Passenger cars, light trucks, heavy trucks, and motorcycles comprise the four main categories of highway vehicles. Within each of these categories, powerplant and fuel variations result in significantly different emission characteristics. For example, heavy trucks may be powered by gasoline or diesel fuel or operate on a gaseous fuel such as compressed natural gas (CNG).

It is important to note that highway vehicle emission factors change with time and, therefore, must be calculated for a specific time period, normally one calendar year. The major reason for this time dependence is the gradual replacement of vehicles without emission control equipment by vehicles with control equipment, as well as the gradual deterioration of vehicles with control equipment as they accumulate age and mileage. The emission factors presented in this chapter cover only calendar years 1971 and 1972 and are based on analyses of actual tests of existing sources and control systems. Projected emission factors for future calendar years are no longer presented in this chapter because projections are "best guesses" and are best presented independently of analytical results. The authors are aware of the necessity for forecasting emissions; therefore, projected emission factors are available in Appendix D of this document.

Highway vehicle emission factors are presented in two forms in this chapter. Section 3.1.1 contains average emission factors for calendar year 1972 for selected values of vehicle miles traveled by vehicle type (passenger cars, light trucks, and heavy trucks), ambient temperature, cold/hot weighting, and average vehicle speed. The section includes one case that represents the average national emission factors as well as thirteen other scenarios that can be used to assess the sensitivity of the composite emission factor to changing input conditions. All emission factors are given in grams of pollutant per kilometer traveled (and in grams of pollutant per mile traveled).

The emission factors given in sections 3.1.2 through 3.1.7 are for individual classes of highway vehicles and their application is encouraged if specific statistical data are available for the area under study. The statistical data required include vehicle registrations by model year and vehicle type, annual vehicle travel in miles or kilometers by vehicle type and age, average ambient temperature, percentage of cold-engine operation by vehicle type, and average vehicle speed. When regional inputs are not available, national values (which are discussed) may be applied.

3.1.1 Average Emission Factors for Highway Vehicles

revised by David S. Kircher
and Marcia E. Williams

3.1.1.1 General–Emission factors presented in this section are intended to assist those individuals interested in compiling approximate mobile source emission estimates for large areas, such as an individual air quality region or the entire nation, for calendar year 1972. Projected mobile source emission factors for future years are no longer presented in this section. This change in presentation was made to assure consistency with the remainder of this publication, which contains emission factors based on actual test results on currently controlled sources and pollutants. Projected average emission factors for vehicles are available, however, in Appendix D of this publication.

The emission factor calculation techniques presented in sections 3.1.2 through 3.1.5 of this chapter are strongly recommended for the formulation of localized emission estimates required for air quality modeling or for the evaluation of air pollutant control strategies. Many factors, which vary with geographic location and estimation situation, can affect emission estimates considerably. The factors of concern include average vehicle speed, percentage of cold vehicle operation, percentage of travel by vehicle category (automobiles, light trucks, heavy trucks), and ambient temperature. Clearly, the infinite variations in these factors make it impossible to present composite mobile source emission factors for each application. An effort has been made, therefore, to present average emission factors for a range of conditions. The following conditions are considered for each of these cases:

Average vehicle speed – Two vehicle speeds are considered. The first is an average speed of 19.6 mi/hr (31.6 km/hr), which should be typical of a large percentage of urban vehicle operation. The second is an average speed of 45 mi/hr (72 km/hr), which should be typical of highway or rural operation.

Percentage of cold operation – Three percentages of cold operation are considered. The first (at 31.6 km/hr) assumes that 20 percent of the automobiles and light trucks are operating in a cold condition (representative of vehicle start-up after a long engine-off period) and that 80 percent of the automobiles and light trucks are operating in a hot condition (warmed-up vehicle operation). This condition can be expected to assess the engine temperature situation over a large area for an entire day. The second situation assumes that 100 percent of the automobiles and light trucks are operating in a hot condition (at 72 km/hr). This might be applicable to rural or highway operation. The third situation (at 31.6 km/hr) assumes that 100 percent of the automobiles and light trucks are operating in a cold condition. This might be a worst-case situation around an indirect source such as a sports stadium after an event lets out. In all three situations, heavy-duty vehicles are assumed to be operating in a hot condition.

Percentage of travel by vehicle type – Three situations are considered. The first (at both 31.6 km/hr and 72 km/hr) involves a nationwide mix of vehicle miles traveled by automobiles, light trucks, heavy gasoline trucks, and heavy diesel trucks. The specific numbers are 80.4, 11.8, 4.6, and 3.2 percent of total vehicle miles traveled, respectively.[1, 2] The second (at 31.6 km/hr) examines a mix of vehicle miles traveled that might be found in a central city area. The specific numbers are 63, 32, 2.5, and 2.5 percent, respectively. The third (31.6 km/hr) examines a mix of vehicles that might be found in a suburban location or near a localized indirect source where no heavy truck operation exist. The specific numbers are 88.2, 11.8, 0, and 0 percent, respectively.

Ambient temperature – Two situations at 31.6 km/hr are considered: an average ambient temperature of 24°C (75°F) and an average ambient temperature of 10°C (50°F).

Table 3.1.1-1 presents composite CO, HC, and NO_X factors for the 13 cases discussed above for calendar year 1972. Because particulate emissions and sulfur oxides emissions are not assumed to be functions of the factors discussed above, these emission factors are the same for all scenarios and are also presented in the table. The table entries were calculated using the techniques described and data presented in sections 3.1.2, 3.1.4, and 3.1.5 of this chapter. Examination of Table 3.1.1-1 can indicate the sensitivity of the composite emission factor to various

Table 3.1.1-1. AVERAGE EMISSION FACTORS FOR HIGHWAY VEHICLES, CALENDAR YEAR 1972
EMISSION FACTOR RATING: B

Scenario						Emission factors for highway vehicles									
Vehicle weight mix	Average route speed,		Ambient temperature,		Cold operation,	Carbon monoxide		Hydrocarbons		Nitrogen oxides		Particulate		Sulfur oxides	
	mi/hr	km/hr	°F	°C	%	g/mi	g/km	g/mi	g/km	g/mi	g/km	g/mi	g/km	g/mi	g/km
National average	19.6	31.6	75	24	20	76.5	47.5	10.8	6.7	4.9	3.0	0.60	0.37	0.23	0.14
			50	10	20	97.1	60.3	13.0	8.1	5.4	3.4	0.60	0.37	0.23	0.14
			75	24	100	145	90.0	14.6	9.1	4.6	2.9	0.60	0.37	0.23	0.14
			50	10	100	228	142	22.4	13.9	4.6	2.9	0.60	0.37	0.23	0.14
No heavy-duty travel	19.6	31.6	75	24	20	70.6	43.8	9.6	6.0	4.2	2.6	0.54	0.34	0.13	0.08
			50	10	20	92.9	57.7	11.3	7.0	4.7	2.9	0.54	0.34	0.13	0.08
			75	24	100	146	90.7	13.8	8.6	3.8	2.4	0.54	0.34	0.13	0.08
			50	10	100	234	145	22.1	13.7	3.8	2.4	0.54	0.34	0.13	0.08
Central City	19.6	31.6	75	24	20	78.2	48.6	11.2	7.0	4.8	3.0	0.60	0.37	0.20	0.12
			50	10	20	101	62.7	13.7	8.5	5.3	3.3	0.60	0.37	0.20	0.12
			75	24	100	154	95.6	15.6	9.7	4.5	2.8	0.60	0.37	0.20	0.12
			50	10	100	245	152	24.5	15.2	4.5	2.8	0.60	0.37	0.20	0.12
National average	45	72.5	75	24	0	29.8	18.5	4.7	2.9	8.0	5.0	0.60	0.37	0.23	0.14

conditions. A user who has specific data on the input factors should calculate a composite factor to fit the exact scenario. When specific input factor data are not available, however, it is hoped that the range of values presented in the table will cover the majority of applications. The user should be sure, however, that the appropriate scenario is chosen to fit the situation under analysis. In many cases, it is not necessary to apply the various temperature, vehicle speed, and cold/hot operation correction factors because the basic emission factors (24°C, 31.6 km/hr, 20 percent cold operation, nationwide mix of travel by vehicle category) are reasonably accurate predictors of motor vehicle emissions on a regionwide (urban) basis.

References for Section 3.1.1

1. Highway Statistics 1971. U.S. Department of Transportation. Federal Highway Administration. Washington, D.C. 1972. p. 81.

2. 1972 Census of Transportation. Truck Inventory and Use Survey. U.S. Department of Commerce. Bureau of the Census. Washington, D.C. 1974.

3.1.2 Light-Duty, Gasoline-Powered Vehicles (Automobiles)

by David S. Kircher,
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3.1.2.1 General – Because of their widespread use, light-duty vehicles (automobiles) are responsible for a large share of air pollutant emissions in many areas of the United States. Substantial effort has been expended recently to accurately characterize emissions from these vehicles.[1,2] The methods used to determined composite automobile emission factors have been the subject of continuing EPA research, and, as a result, two different techniques for estimating CO, HC, and NO_X exhaust emission factors are discussed in this section.

The first method, based on the Federal Test Procedure (FTP),[3,4] is a modification of the procedure that was discussed in this chapter in earlier editions of AP-42. The second and newer procedure, "modal" emissions analysis, enables the user to input a specific driving pattern (or driving "cycle") and to arrive at an emissions rate.[5] The modal technique driving "modes", which include idle, steady-speed cruise, acceleration, and deceleration, are of sufficient complexity that computerization was required. Because of space limitations, the computer program and documentation are not provided in this section but are available elsewhere.[5]

In addition to the methodologies presented for calculating CO, HC, and NO_X exhaust emissions, data are given later in this section for emissions in the idle mode, for crankcase and evaporative hydrocarbon emissions, and for particulate and sulfur oxides emissions.

3.1.2.2 FTP Method for Estimating Carbon Monoxide, Exhaust Hydrocarbons and Nitrogen Oxides Emission Factors – This discussion is begun with a note of caution. At the outset, many former users of this method may be somewhat surprised by the organizational and methodological changes that have occurred. Cause for concern may stem from: (1) the apparent disappearance of "deterioration" factors and (2) the apparent loss of the much-needed capability to project future emission levels. There are, however, substantive reasons for the changes implemented herein.

Results from EPA's annual surveillance programs (Fiscal Years 1971 and 1972) are not yet sufficient to yield a statistically meaningful relationship between emissions and accumulated mileage. Contrary to the previous assumption, emission deterioration can be convincingly related not only to vehicle mileage but also to vehicle age. This relationship may not come as a surprise to many people, but the complications are significant. Attempts to determine a functional relationship between *only* emissions and accumulated mileage have indicated that the data can fit a linear form as well as a non-linear (log) form. Rather than attempting to force the data into a mathematical mold, the authors have chosen to present emission factors by both model year and calendar year. The deterioration factors are, therefore, "built in" to the emission factors. This change simplifies the calculations and represents a realistic, sound use of emission surveillance data.

The second change is organizational: emission factors projected to future years are no longer presented in this section. This is in keeping with other sections of the publication, which contains emission factors only for existing sources based on analyses of test results. As mentioned earlier, projections are "best guesses" and are best presented independently of analytical results (see Appendix D).

The calculation of composite exhaust emission factors using the FTP method is given by:

$$e_{npstw} = \sum_{i=n-12}^{n} c_{ipn} \, m_{in} \, v_{ips} \, z_{ipt} \, r_{iptw} \qquad (3.1.2\text{-}1)$$

where: e_{npstw} = Composite emission factor in g/mi (g/km) for calendar year (n), pollutant (p), average speed (s), ambient temperature (t), and percentage cold operation (w)

c_{ipn} = The FTP (1975 Federal Test Procedure) mean emission factor for the i^{th} model year light-duty vehicles during calendar year (n) and for pollutant (p)

m_{in} = The fraction of annual travel by the i^{th} model year light-duty vehicles during calendar year (n)

v_{ips} = The speed correction factor for the i^{th} model year light-duty vehicles for pollutant (p) and average speed (s)

z_{ipt} = The temperature correction factor for the i^{th} model year light-duty vehicles for pollutant (p) and ambient temperature (t)

r_{iptw} = The hot/cold vehicle operation correction factor for the i^{th} model year light-duty vehicles for pollutant (p), ambient temperature (t), and percentage cold operation (w)

The data necessary to complete this calculation for any geographic area are presented in Tables 3.1.2-1 through 3.1.2-8. Each of the variables in equation 3.1.2-1 is described in greater detail below, after which the technique is illustrated by an example.

Table 3.1.2-1. CARBON MONOXIDE, HYDROCARBON, AND NITROGEN OXIDES EXHAUST EMISSION FACTORS FOR LIGHT-DUTY VEHICLES –EXCLUDING CALIFORNIA–FOR CALENDAR YEAR 1971[a,b]
(BASED ON 1975 FEDERAL TEST PROCEDURE)
EMISSION FACTOR RATING: A

Location and model year	Carbon monoxide		Hydrocarbons		Nitrogen oxides	
	g/mi	g/km	g/mi	g/km	g/mi	g/km
Low altitude						
Pre-1968	86.5	53.7	8.74	5.43	3.54	2.20
1968	67.8	42.1	5.54	3.44	4.34	2.70
1969	61.7	38.3	5.19	3.22	5.45	3.38
1970	47.6	29.6	3.77	2.34	5.15	3.20
1971	39.6	24.6	3.07	1.91	5.06	3.14
High altitude						
Pre-1968	126.9	78.8	10.16	6.31	1.87	1.17
1968	109.2	67.8	7.34	4.59	2.20	1.37
1969	76.4	47.4	6.31	3.91	2.59	1.61
1970	94.8	58.9	6.71	4.17	2.78	1.73
1971	88.0	54.6	5.6	3.48	3.05	1.89

[a] Note: The values in this table can be used to estimate emissions only for calendar year 1971. This reflects a substantial change over past presentation of data in this chapter (see text for details).

[b] References 1 and 2. These references summarize and analyze the results of emission tests of light-duty vehicles in several U.S. cities.

Table 3.1.2-2. CARBON MONOXIDE, HYDROCARBON, AND NITROGEN OXIDES EXHAUST EMISSION FACTORS FOR LIGHT-DUTY VEHICLES–STATE OF CALIFORNIA ONLY–FOR CALENDAR YEAR 1971[a,b]
(BASED ON 1975 FEDERAL TEST PROCEDURE)
EMISSION FACTOR RATING: A

Location and model year	Carbon monoxide		Hydrocarbons		Nitrogen oxides	
	g/mi	g/km	g/mi	g/km	g/mi	g/km
California						
Pre-1966[c]	86.5	53.7	8.74	5.43	3.54	2.20
1966	65.2	40.5	7.84	4.87	3.40	2.11
1967	67.2	41.7	5.33	3.31	3.42	2.12
1968[c]	67.8	42.1	5.54	3.44	4.34	2.70
1969[c]	61.7	38.3	5.19	3.22	5.45	3.38
1970[c]	50.8	31.5	4.45	2.76	4.62	2.87
1971	42.3	26.3	3.02	1.88	3.83	2.38

[a] Note: The values in this table can be used to estimate emissions only for calendar year 1971. This reflects a substantial change past presentations of data in this chapter (see text for details).

[b] References 1. This reference summarizes and analyzes the results of emission tests of light-duty vehicles in Los Angeles as well as five other U.S. cities during 1971-1972.

[c] Data for these model years are mean emission test values for the five low altitude test cities summarized in Reference 1.

Table 3.1.2.-3. CARBON MONOXIDE, HYDROCARBON, AND NITROGEN OXIDES EXHAUST EMISSION FACTORS FOR LIGHT-DUTY VEHICLES–EXCLUDING CALIFORNIA–FOR CALENDAR YEAR 1972[a,b]
(BASED ON 1975 FEDERAL TEST PROCEDURE)
EMISSION FACTOR RATING: A

Location and model year	Carbon monoxide		Hydrocarbons		Nitrogen oxides	
	g/mi	g/km	g/mi	g/km	g/mi	g/km
Low altitude						
Pre-1968	93.5	58.1	8.67	5.38	3.34	2.07
1968	63.7	39.6	6.33	3.93	4.44	2.76
1969	64.2	39.9	4.95	3.07	5.00	3.10
1970	53.2	33.0	4.89	3.04	4.35	2.70
1971	51.1	31.7	3.94	2.45	4.30	2.67
1972	36.9	22.9	3.02	1.88	4.55	2.83
High altitude						
Pre-1968	141.0	87.6	11.9	7.39	2.03	1.26
1968	101.4	63.0	6.89	4.26	2.86	1.78
1969	97.8	60.7	5.97	3.71	2.93	1.82
1970	87.5	54.3	5.56	3.45	3.32	2.06
1971	80.3	49.9	5.19	3.22	2.74	1.70
1972	80.4	50.0	4.75	2.94	3.08	1.91

[a] Note: The values in this table can be used to estimate emissions only for calendar year 1972. This reflects a substantial change over past presentation of data in this chapter (see text for details).

[b] Reference 2. This reference summarizes and analyzes the results of emission tests of light-duty vehicles in six U.S. metropolitan areas during 1972-1973.

Table 3.1.2-4. CARBON MONOXIDE, HYDROCARBON, AND NITROGEN OXIDES EXHAUST EMISSION FACTORS FOR LIGHT-DUTY VEHICLES–STATE OF CALIFORNIA ONLY–FOR CALENDAR YEAR 1972[a,b]
(BASED ON 1975 FEDERAL TEST PROCEDURE)
EMISSION FACTOR RATING: A

Location and model year	Carbon monoxide		Hydrocarbons		Nitrogen oxides	
	g/mi	g/km	g/mi	g/km	g/mi	g/km
California						
Pre-1966[c]	93.5	58.1	8.67	5.38	3.34	2.07
1966	86.9	54.0	7.46	4.63	3.43	2.13
1967	75.4	46.8	5.36	3.33	3.77	2.34
1968[c]	63.7	39.6	6.33	3.93	4.44	2.76
1969[c]	64.2	39.9	4.95	3.07	5.00	3.10
1970	78.5	48.7	6.64	4.12	4.46	2.77
1971	59.7	37.1	3.98	2.47	3.83	2.38
1972	46.7	29.0	3.56	2.21	3.81	2.37

[a] Note: The values in this table can be used to estimate emissions only for calendar year 1972. This represents a substantial change over past presentation of data in this chapter (see text for details).

[b] Reference 2. This reference summarizes and analyzes the results of emission tests of light-duty vehicles in Los Angeles as well as in five other U.S. cities during 1972-1973.

[c] Data for these model years are mean emission test values for the five low altitude test cities summarized in Reference 2.

Table 3.1.2-5. SAMPLE CALCULATION OF FRACTION OF LIGHT-DUTY VEHICLE ANNUAL TRAVEL BY MODEL YEAR[a]

Age, years	1972 Fraction of total vehicles in use nationwide (a)[b]	Average annual miles driven (b)[c]	a x b	1972 Fraction of annual travel (m)[d]
1	0.083	15,900	1,320	0.116
2	0.103	15,000	1,545	0.135
3	0.102	14,000	1,428	0.125
4	0.106	13,100	1,389	0.122
5	0.099	12,200	1,208	0.106
6	0.087	11,300	983	0.086
7	0.092	10,300	948	0.083
8	0.088	9,400	827	0.072
9	0.068	8,500	578	0.051
10	0.055	7,600	418	0.037
11	0.039	6,700	261	0.023
12	0.021	6,700	141	0.012
$\geq$13	0.057	6,700	382	0.033

[a] References 6 and 7.

[b] These data are for July 1, 1972, from Reference 7 and represent the U.S. population of light-duty vehicles by model year for that year only.

[c] Mileage values are the results of at least squares analysis of data in Reference 6.

[d] $m = ab/\Sigma ab$.

Table 3.1.2-6. COEFFICIENTS FOR SPEED CORRECTION FACTORS FOR LIGHT-DUTY VEHICLES[a,b]

Location	Model year	$v_{ips} = e^{(A + BS + CS^2)}$						$v_{ips} = A + BS$	
		Hydrocarbons			Carbon monoxide			Nitrogen oxides	
		A	B	C	A	B	C	A	B
Low altitude (Excluding 1966-1967 Calif.)	1957-1967	0.953	-6.00×10^{-2}	5.81×10^{-4}	0.967	-6.07×10^{-2}	5.78×10^{-4}	0.808	0.980×10^{-2}
California	1966-1967	0.957	-5.98×10^{-2}	5.63×10^{-4}	0.981	-6.22×10^{-2}	6.19×10^{-4}	0.844	0.798×10^{-2}
Low altitude	1968	1.070	-6.63×10^{-2}	5.98×10^{-4}	1.047	-6.52×10^{-2}	6.01×10^{-4}	0.888	0.569×10^{-2}
	1969	1.005	-6.27×10^{-2}	5.80×10^{-4}	1.259	-7.72×10^{-2}	6.60×10^{-4}	0.915	0.432×10^{-2}
	1970	0.901	-5.70×10^{-2}	5.59×10^{-4}	1.267	-7.72×10^{-2}	6.40×10^{-4}	0.843	0.798×10^{-2}
	1971-1972	0.943	-5.92×10^{-2}	5.67×10^{-4}	1.241	-7.52×10^{-2}	6.09×10^{-4}	0.843	0.804×10^{-2}
High altitude	1957-1967	0.883	-5.58×10^{-2}	5.52×10^{-4}	0.721	-4.57×10^{-2}	4.56×10^{-4}	0.602	2.027×10^{-2}
	1968	0.722	-4.63×10^{-2}	4.80×10^{-4}	0.662	-4.23×10^{-2}	4.33×10^{-4}	0.642	1.835×10^{-2}
	1969	0.706	-4.55×10^{-2}	4.84×10^{-4}	0.628	-4.04×10^{-2}	4.26×10^{-4}	0.726	1.403×10^{-2}
	1970	0.840	-5.33×10^{-2}	5.33×10^{-4}	0.835	-5.24×10^{-2}	4.98×10^{-4}	0.614	1.978×10^{-2}
	1971-1972	0.787	-4.99×10^{-2}	4.99×10^{-4}	0.894	-5.54×10^{-2}	4.99×10^{-4}	0.697	1.553×10^{-2}

[a] Reference 8. Equations should not be extended beyond the range of the data (15 to 45 mi/hr; 24 to 72 km/hr). For speed correction factors at low speeds (5 and 10 mi/hr; 8 and 16 km/hr) see Table 3.1.2-7.

[b] The speed correction factor equations and coefficients presented in this table are expressed in terms of english units (miles per hour). In order to perform calculations using the metric system of units, it is suggested that kilometers per hour be first converted to miles per hour (1 km/hr = 0.621 mi/hr). Once speed correction factors are determined, all other calculations can be performed using metric units.

Table 3.1.2-7. LOW AVERAGE SPEED CORRECTION FACTORS FOR LIGHT DUTY VEHICLES[a]

Location	Model year	Carbon monoxide		Hydrocarbons		Nitrogen oxides	
		5 mi/hr (8 km/hr)	10 mi/hr (16 km/hr)	5 mi/hr (8 km/hr)	10 mi/hr (16 km/hr)	5 mi/hr (8 km/hr)	10 mi/hr (16 km/hr)
Low altitude (Excluding 1966-1967 Calif.)	1957-1967	2.72	1.57	2.50	1.45	1.08	1.03
California	1966-1967	1.79	1.00	1.87	1.12	1.16	1.09
Low altitude	1968	3.06	1.75	2.96	1.66	1.04	1.00
	1969	3.57	1.86	2.95	1.65	1.08	1.05
	1970	3.60	1.88	2.51	1.51	1.13	1.05
	1971-1972	4.15	2.23	2.75	1.63	1.15	1.03
High altitude	1957-1967	2.29	1.48	2.34	1.37	1.33	1.20
	1968	2.43	1.54	2.10	1.27	1.22	1.18
	1969	2.47	1.61	2.04	1.22	1.22	1.08
	1970	2.84	1.72	2.35	1.36	1.19	1.11
	1971-1972	3.00	1.83	2.17	1.35	1.06	1.02

[a] Driving patterns developed from CAPE-21 vehicle operation data (Reference 9) were input to the modal emission analysis model (see section 3.1.2.3). The results predicted by the model (emissions at 5 and 10 mi/hr; 8 and 16 km/hr) were divided by FTP emission factors for hot operation to obtain the above results. The above data are approximate and represent the best currently available information.

Table 3.1.2-8. LIGHT-DUTY VEHICLE TEMPERATURE CORRECTION FACTORS AND HOT/COLD VEHICLE OPERATION CORRECTION FACTORS FOR FTP EMISSION FACTORS[a]

Pollutant	Temperature correction (z_{ipt})[b]	Hot/Cold operation correction [f(t)][b]
Carbon monoxide	$-0.0127\,t + 1.95$	$0.0045\,t + 0.02$
Hydrocarbons	$-0.0113\,t + 1.81$	$0.0079\,t + 0.03$
Nitrogen oxides	$-0.0046\,t + 1.36$	$-0.0068\,t + 1.64$

[a] Reference 10. Temperature (t) is expressed in °F. In order to apply these equations, °C must be first converted to °F. The appropriate conversion formula is: $F=(9/5)C + 32$. For temperatures expressed on the Kelvin (K) scale: $F=9/5(K-273.16) + 32$.

[b] The formulae for z_{ipt} enable the correction of the FTP emission factors for ambient temperature effects only. The amount of cold/hot operation is not affected. The formulae for f(t), on the other hand, are part of equation 3.1.2-2 for calculating r_{iptw}. The variable r_{iptw} corrects for cold/hot operation as well as ambient temperature.

Note: z_{ipt} can be applied without r_{iptw}, but not vica versa.

FTP emission factor (c_{ipn}). The results of the first two EPA annual light-duty vehicle surveillance programs are summarized in Tables 3.1.2-1 through 3.1.2-4. These data for calendar years 1971 and 1972 are divided by geographic area into: low altitude (excluding California), high altitude (excluding California), and California only. California emission factors are presented separately because, for several model years, California vehicles have been subject to emission standards that differ from standards applicable to vehicles under the Federal emission control program. For those model year vehicles for which California did not have separate emission standards, the national emission factors are assumed to apply in California as well. Emissions at high altitude are differentiated from those at low altitude to account for the effect that altitude has on air-fuel ratios and concomitant emissions. The tabulated values are applicable to calendar years 1971 and 1972 for each model year.

Fraction of annual travel by model year (m_i). A sample calculation of this variable is presented in Table 3.1.2-5. In the example, nationwide statistics are used, and the fraction of in-use vehicles by model year (vehicle age) is weighted on the basis of the annual miles driven. The calculation may be "localized" to reflect local (county, state, etc.) vehicle age mix, annual miles driven, or both. Otherwise, the national data can be used. The data presented in Table 3.1.2-5 are for calendar year 1972 only; for later calendar years, see Appendix D.

Speed Correction Factors (v_{ips}). Speed correction factors enable the "adjustment" of FTP emission factors to account for differences in average route speed. Because the implicit average route speed of the FTP is 19.6 mi/hr (31.6 km/hr), estimates of emissions at higher or lower average speeds require a correction.

It is important to note the difference between "average route speed" and "steady speed". Average route speed is trip-related and based on a composite of the driving modes (idle, cruise, acceleration, deceleration) encountered, for example, during a typical home-to-work trip. Steady speed is highway facility-oriented. For instance, a group of vehicles traveling over an uncongested freeway link (with a volume to capacity ratio of 0.1, for example) might be traveling at a steady speed of about 55 mi/hr (89 km/hr). Note, however, that steady speeds, even at the link level, are unlikely to occur where resistance to traffic flow occurs (unsynchronized traffic signaling, congested flow, etc.)

In previous revisions to this section, the limited data available for correcting for average speed were presented graphically. Recent research, however, has resulted in revised speed relationships by model year.[8] To facilitate the presentation, the data are given as equations and appropriate coefficients in Table 3.1.2-6. These relationships were developed by performing five major tasks. First, urban driving pattern data collected during the CAPE-10 Vehicle Operations Survey[11] were processed by city and time of day into freeway, non-freeway, and composite speed-mode matrices. Second, a large number of driving patterns were computer-generated for a range of average speeds (15 to 45 mi/hr; 24 to 72 km/mi) using weighted combinations of freeway and non-freeway matrices. Each of these patterns was filtered for "representativeness." Third, the 88 resulting patterns were input (second-by-second speeds) to the EPA modal emission analysis model (see sections 3.1.2.3). The output of the model was estimated emissions for each pattern of 11 vehicle groups (see Table 3.1.2.6 for a listing of these groups). Fourth, a regression analysis was performed to relate estimated emissions to average route speed for each of the 11 vehicle groups. Fifth, these relationships were normalized to 19.6 mi/hr (31.6 km/hr) and summarized in Table 3.1.2-6.

The equations in Table 3.1.2-6 apply only for the range of the data – from 15 to 45 mi/hr (24 to 72 km/hr). Because there is a need, in some situations, to estimate emissions at very low average speeds, correction factors for 5 and 10 mi/hr (8 and 16 km/hr) presented in Table 3.1.2-7 were developed using a method somewhat like that described above, again using the modal emission model. The modal emission model predicts emissions from warmed-up vehicles. The use of this model to develop speed correction factors makes the assumption that a given speed correction factor applies equally well to hot and cold vehicle operation. Estimation of warmed-up idle emissions are presented in section 3.1.2.4 on a gram per minute basis.

Temperature Correction Factor (Z_{ipt}). The 1975 FTP requires that emissions measurements be made within the limits of a relatively narrow temperature band (68 to 86°F). Such a band facilitates uniform testing in laboratories without requiring extreme ranges of temperature control. Present emission factors for motor vehicles are based on data from the standard Federal test (assumed to be at 75°F). Recently, EPA and the Bureau of Mines undertook a test program to evaluate the effect of ambient temperature on motor vehicle exhaust emission levels.[10] The study indicates that changes in ambient temperature result in significant changes in emissions during cold start-up operation. Because many Air Quality Control Regions have temperature characteristics differing considerably from the 68 to 86°F range, the temperature correction factor should be applied. These correction factors, which can be applied between 20 and 80°F, are presented in Table 3.1.2-8. For temperatures outside this range, the appropriate endpoint correction factor should be applied.

Hot/Cold Vehicle Operation Correction Factor (r_{iptw}). The 1975 FTP measures emissions during: a cold transient phase (representative of vehicle start-up after a long engine-off period), a hot transient phase (representative of vehicle start-up after a short engine-off period), and a stabilized phase (representative of warmed-up vehicle operation). The weighting factors used in the 1975 FTP are 20 percent, 27 percent, and 53 percent of total miles (time) in each of the three phases, respectively. Thus, when the 1975 FTP emission factors are applied to a given region for the purpose of accessing air quality, 20 percent of the light-duty vehicles in the area of interest are assumed to be operating in a cold condition, 27 percent in a hot start-up condition, and 53 percent in a hot stabilized condition. For non-catalyst equipped vehicles (all pre-1975 model year vehicles), emissions in the two hot phases are essentially equivalent on a grams per mile (grams per kilometer basis). Therefore, the 1975 FTP emission factor represents 20 percent cold operation and 80 percent hot operation.

Many situations exist in which the application of these particular weighting factors may be inappropriate. For example, light-duty vehicle operation in the center city may have a much higher percentage of cold operation during the afternoon peak when work-to-home trips are at a maximum and vehicles have been standing for 8 hours. The hot/cold vehicle operation correction factor allows the cold operation phase to range from 0 to 100 percent of total light-duty vehicle operations. This correction factor is a function of the percentage of cold operation (w) and the ambient temperature (t). The correction factor is:

$$r_{iptw} = \frac{w + (100\text{-}w)\ f(t)}{20 + 80f(t)} \qquad (3.1.2\text{-}2)$$

where: f(t) is given in Table 3.1.2-8.

Sample Calculation. As a means of further describing the application of equation 3.1.2-1, calculation of the carbon monoxide composite emission factor is provided as an example. To perform this calculation (or any calculation using this procedure), the following questions must be answered:

1. What calendar year is being considered?
2. What is the average vehicle speed in the area of concern?
3. Is the area at low altitude (non-California), in California, or at high altitude?
4. Are localized vehicle mix and/or annual travel data available?
5. Which pollutant is to be estimated? (For non-exhaust hydrocarbons see section 3.1.2.5).
6. What is the ambient temperature (if it does not fall within the 68 to 86°F Federal Test Procedure range)?
7. What percentage of vehicle operation is cold operation (first 500 seconds of operation after an engine-off period of at least 4 hours)?

For this example, the composite carbon monoxide emission factor for 1972 will be estimated for a hypothetical county. Average vehicle speed for the county is assumed to be 30 mi/hr. The county is at low altitude (non-California), and localized vehicle mix/annual travel data are unavailable (nationwide statistics are to be used). The ambient temperature is assumed to be 50°F and the percentage of cold vehicle operation is assumed to be 40 percent. To simplify the presentation, the appropriate variables are entered in the following tabulation.

Model year(s)			Variables, [a]			$(c_{ipn})(m_{in})(v_{ips})$ $(z_{ipt})(r_{iptw})$
	c_{ipn}	m_{in}	v_{ips}	z_{ipt}	r_{iptw}	
Pre-1968	58.1	0.396	0.72	1.315	1.39	30.3
1968	39.6	0.106	0.69	1.315	1.39	5.3
1969	39.9	0.122	0.63	1.315	1.39	5.6
1970	33.0	0.125	0.62	1.315	1.39	4.7
1971	31.7	0.135	0.63	1.315	1.39	4.9
1972	22.9	0.116	0.63	1.315	1.39	3.1
						e_{npstw} = 53.9 g/km

[a] The variable c_{ipn} above is from Table 3.1.2-3, and the variable m_{in} was taken from the sample calculation based on nationwide data, Table 3.1.2-5. The fraction of travel for pre-1968 (6 years old and older) vehicles is the sum of the last eight values in the far right-hand column of the table. The speed correction factor (v_{ips}) was calculated from the appropriate equations in Table 3.1.2-6. The variable z_{ipt} was calculated from the appropriate equation in Table 3.1.2-8. The variable r_{iptw} was calculated using an equation from Table 3.1.2-8 and equation 3.1.2-2.

The resultant composite carbon monoxide emission factor for 1972 for the hypothetical county is 53.9 g/km.

3.1.2.3 Modal Emission Model for Estimating Carbon Monoxide, Hydrocarbons, and Nitrogen Oxides Emission Factors – The modal emission model and allied computer programs permit an analyst to calculate mass emission quantities of carbon monoxide, hydrocarbons, and nitrogen oxides emitted by individual vehicles or groups of vehicles over any specified driving sequence or pattern. The complexity of the model and accompanying computer programs makes presentation of the entire procedure in this publication impractical. Instead, the capabilities and limitations of the model are briefly described in the following paragraphs with the details to be found in a separate report, *Automobile Exhaust Emission Modal Analysis Model.*[5]

The modal emission model was developed because of the well-established fact that emission rates for a particular vehicle depend upon the manner in which it is operated. Stated another way, the emissions from a particular vehicle are a function of the time it spends in each of four general operating modes (idle, cruise, deceleration, acceleration) as well as specific operation within each of the four modes. In many situations, use of the basic FTP emission factors may be sufficient. Certainly, nationwide, statewide, and county-wide emission estimates that involve spatial aggregation of vehicular travel data lend themselves to the FTP method (section 3.1.2.2). There are, however, a relatively large number of circumstances for which an analyst may require emission estimates at a zonal or link level of aggregation. The analyst, for example, may be faced with providing inputs to a carbon monoxide dispersion model, estimating the impact of an indirect source (sports complex, shopping center, etc.), or preparing a highway impact statement. In such instances, the resources may be available to determine the necessary inputs to the modal model either by estimation or field studies. These data are input to the modal model and emission estimates are output.

Although the computer software package is sufficiently flexible to accept any set of input modal emission data, EPA data based on tests of 1020 individual light-duty vehicles (automobiles) that represent variations in model year, manufacture, engine and drive train equipment, accumulated mileage, state of maintenance, attached pollution abatement devices, and geographic location are a part of the package. The user, therefore, need not input any modal emission data. He inputs the driving sequence desired as speed (mi/hr) versus time (sec) in 1-second intervals and specifies the vehicle mix for which emission estimates are desired (vehicles are grouped by model year and geographic location). The output of the model can then be combined with the appropriate traffic volume for the desired time period to yield an emission estimate. The use of the modal emission model to estimate a composite emission factor does not, however, eliminate the need for temperature and cold/hot weighting correction factors. The model predicts emissions from warmed-up vehicles at an ambient temperature of approximately 75°F. The estimate of composite exhaust emission factors using the modal emission model is given by:

$$e_{ptw} = c_p \, a_{pt} \, b_{ptw} \qquad (3.1.2\text{-}3)$$

where: e_{ptw} = Composite emission factor in grams per mile (g/km) for calendar year 1971, pollutant (p), ambient temperature (t), percentage cold operation (w), and the specific driving sequence and vehicle mix specified

c_p = The mean emission factor for pollutant (p) for the specified vehicle mix and driving sequence

a_{pt} = The temperature correction factor for pollutant (p) and temperature (t) for warmed-up operation

b_{ptw} = The hot/cold vehicle operation correction factor for pollutant (p), temperature (t), and percentage cold operation (w)

The data necessary to compute a_{pt} and b_{ptw} are given in Table 3.1.2-9. The modal analysis computer program is necessary to compute c_p.[5]

Table 3.1.2-9. LIGHT-DUTY VEHICLE MODAL EMISSION MODEL CORRECTION FACTORS FOR TEMPERATURE AND COLD/HOT START WEIGHTING[a]

Pollutant	Temperature correction (a_{pt})	Hot/cold temperature correction [f(t)]
Carbon monoxide	1.0	0.0045 t + 0.02
Hydrocarbons	1.0	0.0079 t + 0.03
Nitrogen oxides	−0.0065 t + 1.49	−0.0068 t + 1.64

[a] Reference 10. Temperature is expressed in °F. In order to apply these equations, convert °C to °F (F=9/5C + 32); or °K to °F (F=9/5(K-273.16) + 32).

Temperature Correction Factor (a_{pt}). The modal analysis model predicts emissions at approximately 75°F. The temperature correction factors are expressed in equational form and presented in Table 3.1.2-9.

Hot/Cold Vehicle Operation Correction Factor (b_{ptw}). The modal analysis model predicts emissions during warmed-up vehicle operation, but there are many urban situations for which this assumption is not appropriate. The hot/cold vehicle operation correction factor allows for the inclusion of a specific percentage of cold operation. This correction factor is a function of the percentage of cold operation (w) and the ambient temperature (t). The correction factor is:

$$b_{ptw} = \frac{w + (100-w)f(t)}{100\ f(t)} \qquad (3.1.2\text{-}4)$$

where: f(t) is given in Table 3.1.2-9.

It is important that potential users of modal analysis recognize of the important limitations of the model. Although the model provides the capability of predicting emission estimates for any driving pattern, it can only predict emissions for the vehicle groups that have been tested. Presently this capability is limited to 1971 and older light-duty vehicles. Efforts are underway to add additional model years (1972-1974), and new models will be tested as they become available. Although the model is not directly amenable to projecting future year emissions, it can predict "base" year emissions. Future year emissions can be estimated using the ratio of future year to base year emissions based on FTP composite emission factors. Finally, the technique requires the input of a driving sequence and the use of a computer, and is therefore, more complex and more costly to use than the simple FTP technique (section 3.1.2.1).

The modal procedure discussion in this section is recommended when the user is interested in comparing emissions over several different specific driving scenarios. Such an application will result in more accurate comparisons than can be obtained by the method given in section 3.1.2.2. For other applications where average speed is all that is known or when calendar year to calendar year comparisons are required, the method in section 3.1.2.2 is recommended.

3.1.2.4 Carbon Monoxide, Hydrocarbon, and Nitrogen Oxides Idle Emission Factors – Estimates of emissions during a vehicles' idle operating mode may be appropriate at trip attractions such as shopping centers, airports, sports complexes, etc. Because idle emission factors are expressed (by necessity) in terms of elapsed time, emissions at idle can be estimated using vehicle operating minutes rather than the conventional vehicle miles of travel.

Application of the idle values (Table 3.1.2-10) requires calculation of a composite idle emission factor (c_p) through the use of the variable m_{in}(see section 3.1.2.2) and i_{ip} (idle pollutant p emission factor for the i^{th} model year). The temperature and hot/cold weighting factors presented in Table 3.1.2-9 apply to idle emissions. The tabulated values are based on warmed-up emissions. (For a_{pt}, see Table 3.1.2-9; for b_{ptw}, see Table 3.1.2-9 and equation 3.1.2-4.)

Table 3.1.2-10. CARBON MONOXIDE, HYDROCARBON, AND NITROGEN OXIDES EMISSION FACTORS FOR LIGHT-DUTY VEHICLES IN WARMED-UP IDLE MODE[a]
(grams/minute)

Location and model year(s)	Carbon monoxide	Exhaust hydrocarbons	Nitrogen oxides
Low altitude			
Pre-1968	16.9	1.63	0.08
1968	15.8	1.32	0.12
1969	17.1	1.17	0.12
1970	13.1	0.73	0.13
1971	13.0	0.63	0.11
High altitude			
Pre-1968	18.6	1.83	0.11
1968	16.8	1.09	0.11
1969	16.6	0.90	0.10
1970	16.6	1.13	0.11
1971	16.9	0.80	0.16
California only (low altitude)			
Pre-1966	16.9	1.63	0.08
1966	18.7	1.27	0.07
1967	18.7	1.27	0.07
1968	15.8	1.32	0.12
1969	17.1	1.17	0.12
1970	19.3	0.76	0.28
1971	13.3	0.78	0.18

[a] Reference 12.

The mathematical expression is simply:

$$c_p = \sum_{i=n-12}^{n} i_{ip}\ m_{in}\ a_{pt}\ b_{ptw} \qquad (3.1.2\text{-}5)$$

Because the idle data are from the same data base used to develop the modal analysis procedure, they are subject to the same limitations. Most importantly, idle values cannot be directly used to estimate future emissions.

3.1.2.5 Crankcase and Evaporative Hydrocarbon Emission Factors – In addition to exhaust emission factors, the calculation of hydrocarbon emission from gasoline motor vehicles involves evaporative and crankcase hydrocarbon emission factors. Composite crankcase emissions can be determined using:

$$f_n = \sum_{i=n-12}^{n} h_i\ m_{in} \qquad (3.1.2\text{-}6)$$

where: f_n = The composite crankcase hydrocarbon emission factor for calendar year (n)

h_i = The crankcase emission factor for the i^{th} model year

m_{in} = The weighted annual travel of the i^{th} year during calendar year (n)

Crankcase hydrocarbon emission factor by model year are summarized in Table 3.1.2-11.

The two major sources of evaporative hydrocarbon emissions from light-duty vehicles are the fuel tank and the carburetor system. Diurnal changes in ambient temperature result in expansion of the air-fuel mixture in a partially filled fuel tank. As a result, gasoline vapor is expelled to the atmosphere. Running losses from the fuel tank occur as the fuel is heated by the road surface during driving, and hot-soak losses from the carburetor system occur after engine shut down at the end of a trip. These carburetor losses are from locations such as: the

Table 3.1.2-11. CRANKCASE HYDROCARBON EMISSIONS BY MODEL YEAR FOR LIGHT-DUTY VEHICLES EMISSION FACTOR RATING: B

Model year	Hydrocarbons g/mi	Hydrocarbons g/km
California only		
Pre-1961	4.1	2.5
1961 through 1963	0.8	0.5
1964 through 1967	0.0	0.0
Post-1967	0.0	0.0
All areas except California		
Pre-1963	4.1	2.5
1963 through 1967	0.8	0.5
Post-1967	0.0	0.0

[a] Reference 13.

carburetor vents, the float bowl, and the gaps around the throttle and choke shafts. Because evaporative emissions are a function of the diurnal variation in ambient temperature and the number of trips per day, emissions are best calculated in terms of evaporative emissions per day per vehicle. Emissions per day can be converted to emissions per mile (if necessary) by dividing by an average daily miles per vehicle value. This value is likely to vary from location to location, however. The composite evaporative hydrocarbon emission factor is given by:

$$e_n = \sum_{i=n-12}^{n} (g_i + k_i d)\ (m_i) \qquad (3.1.2\text{-}7)$$

where: e_n = The composite evaporative hydrocarbon emission factor for calendar year (n) in 1b/day (g/day)

g_i = The diurnal evaporative hydrocarbon emission factor for model year (i) in 1b/day (g/day)

k_i = The hot soak evaporative emission factor in 1b/trip (g/trip) for the i^{th} model year

d = The number of daily trips per vehicle (3.3 trips/vehicle-day is the nationwide average)

m_i = The fraction of annual travel by the i^{th} model year during calendar year n

The variables g_i and k_i are presented in Table 3.1.2-12 by model year.

Table 3.1.2-12. EVAPORATIVE HYDROCARBON EMISSION FACTORS BY MODEL YEAR FOR LIGHT-DUTY VEHICLES[a]
EMISSION FACTOR RATING: A

Location and model year	By source[b]		Composite emissions[c]		
	Diurnal, g/day	Hot soak, g/trip	g/day	g/mi	g/km
Low altitude					
Pre-1970	26.0	14.7	74.5	2.53	1.57
1970 (Calif.)	16.3	10.9	52.3	1.78	1.11
1970 (non-Calif.)	26.0	14.7	74.5	2.53	1.57
1971	16.3	10.9	52.3	1.78	1.11
1972	12.1	12.0	51.7	1.76	1.09
High altitude[d]					
Pre-1971	37.4	17.4	94.8	3.22	2.00
1971-1972	17.4	14.2	64.3	2.19	1.36

[a] References 1, 14 and 15.

[b] See text for explanation.

[c] Gram per day values are diurnal emissions plus hot soak emisssions multiplied by the average number of trips per day. Nationwide data from References 16 and 17 indicate that the average vehicle is used for 3.3 trips per day. Gram per mile values were determined by dividing average g/day by the average nationwide travel per vehicle (29.4 mi/day) from Reference 16.

[d] Vehicles without evaporative control were not tested at high altitude. Values presented here are the product of the ratio of pre-1971 (low altitude) evaporative emissions to 1972 evaporative emissions and 1971-1972 high altitude emissions.

3.1.2.6 Particulate and Sulfur Oxide Emissions – Light-duty, gasoline-powered vehicles emit relatively small quantities of particulate and sulfur oxides in comparison with the emissions of the three pollutants discussed above. For this reason, average rather than composite emission factors should be sufficiently accurate for approximating particulate and sulfur oxide emissions from light-duty, gasoline-powered vehicles. Average emission factors for these pollutants are presented in Table 3.1.2-13. No Federal standards for these two pollutants are presently in effect, although many areas do have opacity (antismoke) regulations applicable to motor vehicles.

Table 3.1.2-13. PARTICULATE AND SULFUR OXIDES EMISSION FACTORS FOR LIGHT-DUTY VEHICLES
EMISSION FACTOR RATING: C

Pollutant	Emissions for Pre-1973 vehicles	
	g/mi	g/km
Particulate[a]		
Exhaust	0.34	0.21
Tire wear	0.20	0.12
Sulfur oxides[b] (SO_x as SO_2)	0.13	0.08

[a] References 18, 19, and 20.

[b] Based on an average fuel consumption of 13.6 mi/gal (5.8 km/liter) from Reference 21 and on the use of a fuel with a 0.032 percent sulfur content from References 22 through 24 and a density of 6.1 lb/gal (0.73 kg/liter) from References 22 and 23.

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3.1.3 Light-Duty, Diesel-Powered Vehicles

by David S. Kircher

3.1.3.1 General – In comparison with the conventional, "uncontrolled," gasoline-powered, spark-ignited, automotive engine, the uncontrolled diesel automotive engine is a low pollution powerplant. In its uncontrolled form, the diesel engine emits (in grams per mile) considerably less carbon monoxide and hydrocarbons and somewhat less nitrogen oxides than a comparable uncontrolled gasoline engine. A relatively small number of light-duty diesels are in use in the United States.

3.1.3.2 Emissions – Carbon monoxide, hydrocarbons, and nitrogen oxides emission factors for the light-duty, diesel-powered vehicle are shown in Table 3.1.3-1. These factors are based on tests of several Mercedes 220D automobiles using a slightly modified version of the Federal light-duty vehicle test procedure.[1,2] Available automotive diesel test data are limited to these results. No data are available on emissions versus average speed. Emissions from light-duty diesel vehicles during a calendar year (n) and for a pollutant (p) can be approximately calculated using:

$$e_{np} = \sum_{i=n-12}^{n} c_{ipn} \, m_{in} \qquad (3.1.2\text{-}1)$$

where: e_{np} = Composite emission factor in grams per vehicle mile for calendar year (n) and pollutant (p)

c_{ipn} = The 1975 Federal test procedure emission rate for pollutant (p) in grams/mile for the i^{th} model year at calendar year (n) (Table 3.1.3-1)

m_{in} = The fraction of total light-duty diesel vehicle miles driven by the i^{th} model year diesel light-duty vehicles

Details of this calculation technique are discussed in section 3.1.2.

The emission factors in Table 3.1.3-1 for particulates and sulfur oxides were developed using an average sulfur content fuel in the case of sulfur oxides and the Dow Measuring Procedure on the 1975 Federal test cycle for particulate.[1,6]

Table 3.1.3-1. EMISSION FACTORS FOR LIGHT-DUTY, DIESEL-POWERED VEHICLES
EMISSION FACTOR RATING: B

Pollutant	Emission factors, Pre-1973 model years	
	g/mi	g/km
Carbon monoxide[a]	1.7	1.1
Exhaust hydrocarbons	0.46	0.29
Nitrogen oxides[a,b] (NO_x as NO_2)	1.6	0.99
Particulate[b]	0.73	0.45
Sulfur oxides[c]	0.54	0.34

[a] Estimates are arithmetic mean of tests of vehicles, References 3 through 5 and 7.

[b] Reference 4.

[c] Calculated using the fuel consumption rate reported in Reference 7 and assuming the use of a diesel fuel containing 0.20 percent sulfur.

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3.1.4 Light-Duty, Gasoline-Powered Trucks and Heavy-Duty, Gasoline-Powered Vehicles

by David S. Kircher
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3.1.4.1 General – This vehicle category consists of trucks and buses powered by gasoline-fueled, spark-ignited internal combustion engines that are used both for commercial purposes (heavy trucks and buses) and personal transportation (light trucks). In addition to the use classification, the categories cover different gross vehicle weight (GVW) ranges. Light trucks range from 0 to 8500 pounds GVW (0 to 3856 kg GVW); heavy-duty vehicles have GVWs of 8501 pounds (3856 kg) and over. The light-duty truck, because of its unique characteristics and usage, is treated in a separate category in this revision to AP-42. Previously, light trucks with a GVW of 6000 pounds (2722 kg) or less were included in section 3.1.2 (Light-Duty, Gasoline-Powered Vehicles), and light trucks with a GVW of between 6001 and 8500 pounds (2722-3855 kg) were included in section 3.1.4 (Heavy-Duty, Gasoline-Powered Vehicles).

3.1.4.2 Light-Duty Truck Emissions – Because of many similarities to the automobile, light truck emission factor calculations are very similar to those presented in section 3.1.2. The most significant difference is in the Federal Test Procedure emission rate.

3.1.4.2.1. Carbon monoxide, hydrocarbon and nitrogen oxides emissions – The calculation of composite exhaust emission factors using the FTP method is given by:

$$e_{npstw} = \sum_{i=n-12}^{n} c_{ipn} \, m_{in} \, v_{ips} \, z_{ipt} \, r_{iptw} \qquad (3.1.4\text{-}1)$$

where: e_{npstw} = Composite emission factor in g/mi (g/km) for calendar year (n), pollutant (p), average speed (s), ambient temperature (t), and percentage cold operation (w)

c_{ipn} = The FTP (1975 Federal Test Procedure) mean emission factor for the i_{th} model year light-duty trucks during calendar year (n) and for pollutant (p)

m_{in} = The fraction of annual travel by the i^{th} model year light-duty trucks during calendar year (n)

v_{ips} = The speed correction factor for the i^{th} model year light-duty trucks for pollutant (p) and average speed (s)

z_{ipt} = The temperature correction for the i^{th} model year light-duty trucks for pollutant (p) and ambient temperature (t)

r_{iptw} = The hot/cold vehicle operation correction factor for the i_{th} model year light-duty trucks for pollutant (p), ambient temperature (t), and percentage of cold operation (w)

The data necessary to complete this calculation for any geographic area are presented in Tables 3.1.4-1 through 3.1.4-5. Each of the variables in equation 3.1.4-1 is described in greater detail below. The technique is illustrated, by example, in section 3.1.2.

Table 3.1.4-1. EXHAUST EMISSION FACTORS FOR LIGHT-DUTY, GASOLINE-POWERED TRUCKS FOR CALENDAR YEAR 1972
EMISSION FACTOR RATING: B

Location	Model year	Carbon monoxide		Exhaust hydrocarbons		Nitrogen oxides	
		g/mi	g/km	g/mi	g/km	g/mi	g/km
All areas except high altitude and California[a]	Pre-1968[a]	125	77.6	17.0	10.6	4.2	2.6
	1968	66.5	41.3	7.1	4.4	4.9	3.0
	1969	64.3	39.9	5.3	3.3	5.3	3.3
	1970	53.5	33.2	4.8	3.0	5.2	3.2
	1971	53.5	33.2	4.2	2.6	5.2	3.2
	1972	42.8	26.6	3.4	2.1	5.3	3.3
High altitude[b]	Pre-1968	189	117	23.3	14.5	2.6	1.6
	1968	106	65.8	9.7	6.0	3.2	2.0
	1969	98.0	60.9	6.4	4.0	3.1	1.9
	1970	88.0	54.6	5.5	3.4	4.0	2.5
	1971	84.1	52.2	5.5	3.4	3.3	2.0
	1972	84.1	52.2	5.3	3.3	3.6	2.2

[a] References 1 through 4. California emission factors can be estimated as follows:

1. Use pre-1968 factors for all pre-1966 California light trucks.
2. Use 1968 factors for all 1966-1968 California light trucks.
3. For 1969-1972, use the above values multiplied by the ratio of California LDV emission factors to low altitude LDV emission factors (see section 3.1.2).

[b] Based on light-duty emission factors at high altitude compared with light-duty emission factors at low altitude (section 3.1.2).

Table 3.1.4-2. COEFFICIENTS FOR SPEED ADJUSTMENT CURVES FOR LIGHT-DUTY TRUCKS[a]

Location	Model year	$v_{ips} = e^{(A + BS + CS^2)}$						$v_{ips} = A + BS$	
		Hydrocarbons			Carbon monoxide			Nitrogen oxides	
		A	B	C	A	B	C	A	B
Low altitude (Excluding 1966-1967 Calif.)	1957-1967	0.953	-6.00×10^{-2}	5.81×10^{-4}	0.967	-6.07×10^{-2}	5.78×10^{-4}	0.808	0.980×10^{-2}
California Low altitude	1966-1967	0.957	-5.98×10^{-2}	5.63×10^{-4}	0.981	-6.22×10^{-2}	6.19×10^{-4}	0.844	0.798×10^{-2}
	1968	1.070	-6.63×10^{-2}	5.98×10^{-4}	1.047	-6.52×10^{-2}	6.01×10^{-4}	0.888	0.569×10^{-2}
	1969	1.005	-6.27×10^{-2}	5.80×10^{-4}	1.259	-7.72×10^{-2}	6.60×10^{-4}	0.915	0.432×10^{-2}
	1970	0.901	-5.70×10^{-2}	5.59×10^{-4}	1.267	-7.72×10^{-2}	6.40×10^{-4}	0.843	0.798×10^{-2}
	1971-1972	0.943	-5.92×10^{-2}	5.67×10^{-4}	1.241	-7.52×10^{-2}	6.09×10^{-4}	0.843	0.804×10^{-2}
High altitude	1957-1967	0.883	-5.58×10^{-2}	5.52×10^{-4}	0.721	-4.57×10^{-2}	4.56×10^{-4}	0.602	2.027×10^{-2}
	1968	0.722	-4.63×10^{-2}	4.80×10^{-4}	0.662	-4.23×10^{-2}	4.33×10^{-4}	0.642	1.835×10^{-2}
	1969	0.706	-4.55×10^{-2}	4.84×10^{-4}	0.628	-4.04×10^{-2}	4.26×10^{-4}	0.726	1.403×10^{-2}
	1970	0.840	-5.33×10^{-2}	5.33×10^{-4}	0.835	-5.24×10^{-2}	4.98×10^{-4}	0.614	1.978×10^{-2}
	1971-1972	0.787	-4.99×10^{-2}	4.99×10^{-4}	0.894	-5.54×10^{-2}	4.99×10^{-4}	0.697	1.553×10^{-2}

[a] Reference 5. Equations should not be extended beyond the range of data (15 to 45 mi/hr). These data are for light-duty vehicles and are assumed applicable to light-duty trucks.

Table 3.1.4-3. LOW AVERAGE SPEED CORRECTION FACTORS FOR LIGHT-DUTY TRUCKS[a]

Location	Model year	Carbon monoxide		Hydrocarbons		Nitrogen oxides	
		5 mi/hr (8 km/hr)	10 mi/hr (16 km/hr)	5 mi/hr (8 km/hr)	10 mi/hr (16 km/hr)	5 mi/hr (8 km/hr)	10 mi/hr (16 km/hr)
Low altitude (Excluding 1966-1967 Calif.)	1957-1967	2.72	1.57	2.50	1.45	1.08	1.03
California	1966-1967	1.79	1.00	1.87	1.12	1.16	1.09
Low altitude	1968	3.06	1.75	2.96	1.66	1.04	1.00
	1969	3.57	1.86	2.95	1.65	1.08	1.05
	1970	3.60	1.88	2.51	1.51	1.13	1.05
	1971-1972	4.15	2.23	2.75	1.63	1.15	1.03
High altitude	1957-1967	2.29	1.48	2.34	1.37	1.33	1.20
	1968	2.43	1.54	2.10	1.27	1.22	1.18
	1969	2.47	1.61	2.04	1.22	1.22	1.08
	1970	2.84	1.72	2.35	1.36	1.19	1.11
	1971-1972	3.00	1.83	2.17	1.35	1.06	1.02

[a] Driving patterns developed from CAPE-21 vehicle operation data (Reference 6) were input to the modal emission analysis model (see section 3.1.2.3). The results predicted by the model (emissions at 5 and 10 mi/hr; 8 and 16 km/hr) were divided by FTP emission factors for hot operation to obtain the above results. The above data are approximate and represent the best currently available information.

Table 3.1.4-4. SAMPLE CALCULATION OF FRACTION OF ANNUAL LIGHT-DUTY TRUCK TRAVEL BY MODEL YEAR[a]

Age, years	Fraction of total vehicles in use nationwide (a)[b]	Average annual miles driven (b)	a x b	Fraction of annual travel (m)[c]
1	0.061	15,900	970	0.094
2	0.095	15,000	1,425	0.138
3	0.094	14,000	1,316	0.127
4	0.103	13,100	1,349	0.131
5	0.083	12,200	1,013	0.098
6	0.076	11,300	859	0.083
7	0.076	10,300	783	0.076
8	0.063	9,400	592	0.057
9	0.054	8,500	459	0.044
10	0.043	7,600	327	0.032
11	0.036	6,700	241	0.023
12	0.024	6,700	161	0.016
≥13	0.185	4,500	832	0.081

[a] Vehicles in use by model year as of 1972 (Reference 7).

[b] References 7 and 8.

[c] $m = ab/\Sigma ab$.

Table 3.1.4-5. LIGHT-DUTY TRUCK TEMPERATURE CORRECTION FACTORS AND HOT/COLD VEHICLE OPERATION CORRECTION FACTORS FOR FTP EMISSION FACTORS[a]

Pollutant	Temperature correction (z_{ipt})[b]	Hot/cold operation correction [f(t)][b]
Carbon monoxide	$-0.0127\,t + 1.95$	$0.0045\,t + 0.02$
Hydrocarbons	$-0.0113\,t + 1.81$	$0.0079\,t + 0.03$
Nitrogen oxides	$-0.0046\,t + 1.36$	$-0.0068\,t + 1.64$

[a] Reference 9. Temperature (t) is expressed in °F. In order to apply these equations, °C must be first converted to °F. The appropriate conversion formula is: $F = (9/5)C + 32$. For temperatures expressed on the Kelvin (K) scale: $F = 9/5\,(K - 273.16) + 32$.

[b] The formulae for z_{ipt} enable the correction of the FTP emission factors for ambient temperature effects only. The amount of cold/hot operation is not affected. The formulae for f(t), on the other hand, are part of equation 3.1.4-2 for calculating r_{iptw}. The variable r_{iptw} corrects for cold/hot operation as well as ambient temperature. Note: z_{ipt} can be applied without r_{iptw}, but not vice versa.

FTP Emission Factor (c_{ipn}). The results of the EPA light-duty truck surveillance programs are summarized in Table 3.1.4-1. These data are divided by geographic area into: low altitude (non-California), high altitude, and California only. California emission factors are presented separately (as a footnote) because light-duty trucks operated in California have been, in the case of several model years, subject to emission standards that differ from those standards applicable to light trucks under the Federal emission control program. Emissions at high altitude are differentiated from those at low altitude to account for the effect that altitude has on air-fuel ratios and concomitant emissions. The tabulated values are applicable to calendar year 1972 for each model year.

Fraction of Annual Travel by Model Year (m_{in}). A sample calculation of this variable is presented in Table 3.1.4-4. In the example, nationwide statistics are used and the fraction of in-use vehicles by model year (vehicle age) are weighted on the basis of the annual miles driven (again, nationwide data are used). The calculation may be "localized" to reflect local (county, state, etc.) vehicle age mix, annual miles driven, or both. Otherwise, the national data can be used. The data presented in Table 3.1.4-3 are for calendar year 1972 only; for later calendar years, see Appendix D.

Speed Correction Factors (v_{ips}). Speed correction factors enable the "adjustment" of FTP emission factors to account for differences in average route speed. Because the implicit average route speed of the FTP is 19.6 mi/hr (31.6 km/hr), estimates of emissions at higher or lower average speeds require a correction.

It is important to note the difference between "average route speed" and "steady speed." Average route speed is trip-related and based on a composite of the driving modes (idle, cruise, acceleration, deceleration) encountered during a typical home-to-work trip, for example. Steady speed is highway-facility-oriented. For instance, a group of vehicles traveling over an uncongested freeway link (with a volume to capacity ratio of 0.1, for example) might be traveling at a steady speed of about 55 mi/hr (89 km/hr). Note, however, that steady speeds, even at the link level, are unlikely to occur where resistance to traffic flow occurs (unsynchronized traffic signaling, congested flow, etc.).

In previous revisions to this section, the limited data available for correcting for average speed were presented graphically. Recent research however, resulted in revised speed relationships by model year.[5] To facilitate the presentation, the data are given as equations and appropriate coefficients in Table 3.1.4-2. These relationships were developed by performing five major tasks. First, urban driving pattern data collected during the CAPE-10 Vehicle Operation Survey[10] were processed by city and time of day into freeway, non-freeway, and composite speed-mode matrices. Second, a large number of driving patterns were computer-generated for a range of average speeds (15 to 45 mi/hr; 24 to 72 km/hr) using weighted combinations of freeway and non-freeway matrices. Each of these patterns was filtered for "representativeness." Third, the 88 resulting patterns were input (second by second speeds) to the EPA modal emission analysis model (see 3.1.2.3).[11] The output of the model was estimated emissions for each of 11 vehicle groups (see Table 3.1.4-2 for a listing of these groups). Fourth, a regression analysis was performed to relate estimated emissions to average route speed for each of the 11 vehicle groups. Fifth, these relationships were normalized to 19.6 mi/hr (31.6 km/hr) and summarized in Table 3.1.4-2.

The equations in Table 3.1.4-2 apply only for the range of the data – from 15 to 45 mi/hr (24 to 72 km/hr). Because of the need, in some situations, to estimate emissions at very low average speeds, correction factors have been developed for this purpose. The speed correction factors for 5 and 10 mi/hr (8 and 16 km/hr) presented in Table 3.1.4-3 were developed using a method somewhat like that described above, again using the modal emission model. Because the modal emission model predicts warmed-up vehicle emissions, the use of this model to develop speed correction factors makes the assumption that a given speed correction factor applies equally well to hot and cold vehicle operation.

Temperature Correction Factor (z_{ipt}). The 1975 FTP requires that emission measurements be made within the limits of a relatively narrow temperature band (68 to 86°F). Such a band facilitates uniform testing in laboratories without requiring extreme ranges of temperature control. Present emission factors for motor vehicle are based on data from the standard Federal test (assumed to be at 75°F). Recently, EPA and the Bureau of Mines undertook a test program to evaluate the effect of ambient temperatures on motor vehicle exhaust emissions levels.[9] The study indicates that changes in ambient temperature result in significant changes in emissions during cold start-up operation. Because many Air Quality Control Regions have temperature characteristics differing considerably from the 68 to 86°F range, the temperature correction factor should be applied. The corrections factors are expressed in equational form and presented in Table 3.1.4-5 and can be applied between 20 and 80°F. For temperatures outside this range, the appropriate endpoint correction factor should be applied.

Hot/Cold Vehicle Operation Correction Factor (r_{iptw}). The 1975 FTP measures emissions over three types of driving: a cold transient phase (representative of vehicle start-up after a long engine-off period), a hot transient phase (representative of vehicle start-up after a short engine-off period), and a stabilized phase (representative of warmed-up vehicle operation). The weighting factors used in the 1975 FTP are 20 percent, 27 percent, and 53 percent of total miles (time) in each of the three phases, respectively. Thus, when the 1975 FTP emission factors are applied to a given region for the purpose of assessing air quality, 20 percent of the light-duty trucks in the area of interest are assumed to be operating in a cold condition, 27 percent in a hot start-up condition, and 53 percent in a hot stabilized condition. For non-catalyst equipped vehicles (all pre-1975 model year vehicles), emission in the two hot phases are essentially equivalent on a grams per mile (g/km) basis. Therefore, the 1975 FTP emission factor represents 20 percent cold operation and 80 percent hot operation.

Many situations exist in which the application of these particular weighting factors may be inappropriate. For example, light-duty truck operation in center city areas may have a much higher percentage of cold operation during the afternoon pollutant emissions peak when work-to-home trips are at a maximum and vehicles have been standing for 8 hours. The hot/cold vehicle operation correction factor allows the cold operation phase to range from 0 to 100 percent of total light-duty truck operations. This correction factor is a function of the percentage of cold operation (w) and the ambient temperature (t). The correction factor is:

$$r_{iptw} = \frac{w+(100-w)f(t)}{20+80f(t)} \qquad (3.1.4\text{-}2)$$

where: f(t) is given in Table 3.1.4-5.

3.1.4.2.2 Crankcase and evaporative hydrocarbon emissions – Evaporative and crankcase hydrocarbon emissions are determined using:

$$f_n = \sum_{i=n-12}^{n} h_i \, m_{in} \qquad (3.1.4\text{-}3)$$

where: f_n = The combined evaporative and crankcase hydrocarbon emission factor for calendar year (n)

h_i = The combined evaporative and crankcase hydrocarbon emission rate for the i^{th} model year. Emission factors for this source are reported in Table 3.1.4-6. The crankcase and evaporative emissions reported in the table are added together to arrive at this variable.

m_{in} = The weighted annual travel of the i^{th} model year vehicle during calendar year (n)

Table 3.1.4-6. CRANKCASE AND EVAPORATIVE HYDROCARBON EMISSION FACTORS FOR LIGHT-DUTY, GASOLINE-POWERED TRUCKS
EMISSION FACTOR RATING: B

Location	Model years	Crankcase emissions[a]		Evaporative emissions[b]	
		g/mi	g/km	g/mi	g/km
All areas except high altitude and California[c]	Pre-1963	4.6	2.9	3.6	2.2
	1963-1967	2.4	1.5	3.6	2.2
	1968-1970	0.0	0.0	3.6	2.2
	1971	0.0	0.0	3.1	1.9
	1972	0.0	0.0	3.1	1.9
High altitude	Pre-1963	4.6	2.9	4.6	2.9
	1963-1967	2.4	1.5	4.6	2.9
	1968-1970	0.0	0.0	4.6	2.9
	1971-1972	0.0	0.0	3.9	2.4

[a] Reference 12. Tabulated values were determined by assuming that two-thirds of the light-duty trucks are 6000 lbs GVW (2700 kg) and under and that one-third are 6001 to 8500 lbs GVW (2700 to 3860 kg).

[b] Light-duty vehicle evaporative data (section 3.1.2) and heavy-duty vehicle evaporative data (Table 3.1.4-8) were used to estimate the values.

[c] For California: Evaporative emissions for the 1970 model year are 1.9 g/km (3.1 g/mi). All other model years are the same as those reported as "All areas except high altitude and California." Crankcase emissions for the pre-1961 California light-duty trucks are 4.6 g/mi (2.9 g/km) and 1961-1963 models years are 2.4 g/mi (1.5 g/km) all post-1963 model year vehicles are 0.0 g/mi (0.0 g/km).

3.1.4.2.3 Sulfur oxide and particulate emissions – Sulfur oxide and particulate emission factors for all model year light trucks are presented in Table 3.1.4-7. Sulfur oxides factors are based on fuel sulfur content and fuel consumption. Tire-wear particulate factors are based on automobile test results, a premise necessary because of the lack of data. Light truck tire wear is likely to result in greater particulate emissions than automobiles because of larger tires and heavier loads on tires.

Table 3.1.4-7. PARTICULATE AND SULFUR OXIDES EMISSION FACTORS FOR LIGHT-DUTY, GASOLINE-POWERED TRUCKS
EMISSION FACTOR RATING: C

Pollutant	Emissions, Pre-1973 vehicles	
	g/mi	g/km
Particulate[a]		
Exhaust	0.34	0.21
Tire wear[b]	0.20	0.12
Sulfur oxides[c] (SO_x as SO_2)	0.18	0.11

[a] References 13 and 14. Based on tests of automobiles.

[b] Reference 14 summarized tests of automotive tire wear particulate. It is assumed that light-duty truck emissions are similar. The automotive tests assume a four-tire vehicle. If corrections for vehicles with a greater number of tires are needed, multiply the above value by the number of tires and divide by four.

[c] Based on an average fuel consumption 10.0 mi/gal (4.3 km/liter) from Reference 15 and on the use of a fuel with a 0.032 percent sulfur content from References 17 and 18 and a density of 6.1 lb/gal (0.73 kg/liter) from References 17 and 18.

3.1.4.3 Heavy-Duty Vehicle Emissions – Emissions research on heavy-duty, gasoline-powered vehicles has been limited in contrast to that for light-duty vehicles and light-duty trucks. As a result, cold operation correction factors, temperature correction factors, speed correction factors, idle emission rates, etc. are not available for heavy-duty vehicles. For some of these variables, however, light-duty vehicle data can be applied to heavy-duty vehicles. In instances in which light-duty vehicle data are not appropriate, a value of unity if assumed.

3.1.4.3.1 Carbon monoxide, hydrocarbon, and nitrogen oxides emissions – The calculation of heavy-duty, gasoline-powered vehicle exhaust emission factors can be accomplished using:

$$e_{nps} = \sum_{i=n-12}^{n} c_{ipn} \, m_{in} \, v_{ips} \qquad (3.1.4\text{-}4)$$

where: e_{nps} = Composite emission factor in grams per mile (grams per kilometer) for calendar year (n) and pollutant (p) and average speed(s)

c_{ipn} = The test procedure emission rate (Table 3.1.4-8) for pollutant (p) in g/mi (g/km) for the i^{th} model year in calendar year (n)

m_{in} = The weighted annual travel of the i^{th} model year vehicles during calendar year (n). The determination of this variable involves the use of the vehicle year distribution.

v_{ips} = The speed correction factor for the i^{th} model year vehicles for pollutant (p) and average speed(s)

Table 3.1.4-8. EXHAUST EMISSION FACTORS FOR HEAVY-DUTY, GASOLINE-POWERED TRUCKS FOR CALENDAR YEAR 1972[a]
EMISSION FACTOR RATING: B

Location	Model year	Carbon monoxide		Exhaust hydrocarbons		Nitrogen oxides	
		g/mi	g/km	g/mi	g/km	g/mi	g/km
All areas except high altitude	Pre-1970	238	148	35.4	22.0	6.8	4.2
	1970	188	117	13.8	8.6	12.6	7.8
	1971	188	117	13.7	8.5	12.6	7.8
	1972	188	117	13.6	8.4	12.5	7.8
High altitude only[b]	Pre-1970	359	223	48.6	30.2	4.1	2.5
	1970	299	186	15.0	9.3	8.1	5.0
	1971	299	186	14.9	9.3	8.1	5.0
	1972	299	186	14.8	9.2	8.1	5.0

[a] Data from References 19 and 20.

[b] Based on light-duty emissions at high altitude compared with light-duty emissions at low altitudes.

A brief discussion of the variables presented in the above equation is necessary to help clarify their formulation and use. The following paragraphs further describe the variables c_{ipn}, m_{in}, and v_{ips} as they apply to heavy-duty, gasoline-powered vehicles.

Test procedure emission factor (c_{ipn}). The emission factors for heavy-duty vehicles (Table 3.1.4-8) for all areas are based on tests of vehicles operated on-the-road over the San Antonio Road Route (SARR). The SARR, located in San Antonio, Texas, is 7.24 miles long and includes freeway, arterial, and local/collector highway segments.[19] A constant volume sampler is carried on board each of the test vehicles for collection of a proportional part of the exhaust gas from the vehicle. This sample is later analyzed to yield mass emission rates. Because the SARR is an actual road route, the average speed varies depending on traffic conditions at the time of the test. The average speed tends to be around 18 mi/hr (29 km/hr) with about 20 percent of the time spent at idle. The test procedure emission factor is composed entirely of warmed-up vehicle operation. Based on preliminary analysis of vehicle operation data[6], almost all heavy-duty vehicle operation is under warmed-up conditions.

Weighted annual mileage (m_{in}). The determination of this variable is illustrated in Table 3.1.4-9. For purposes of this illustration, nation-wide statistics have been used. Localized data, if available, should be substituted when calculating the variable m_{in} for a specific area under study.

Table 3.1.4-9. SAMPLE CALCULATION OF FRACTION OF GASOLINE-POWERED, HEAVY-DUTY VEHICLE ANNUAL TRAVEL BY MODEL YEAR[a]

Age, years	Fraction of total vehicles in use nationwide (a)[b]	Average annual miles driven (b)	a x b	Fraction of annual travel (m)[c]
1	0.037	19,000	703	0.062
2	0.070	18,000	1,260	0.111
3	0.078	17,000	1,326	0.117
4	0.086	16,000	1,376	0.122
5	0.075	14,000	1,050	0.093
6	0.075	12,000	900	0.080
7	0.075	10,000	750	0.066
8	0.068	9,500	646	0.057
9	0.059	9,000	531	0.047
10	0.053	8,500	451	0.040
11	0.044	8,000	352	0.031
12	0.032	7,500	240	0.021
$\geq$13	0.247	7,000	1,729	0.153

[a] Vehicles in use by model year as of 1972 (Reference 7).
[b] Reference 7.
[c] $m = ab/\Sigma ab$.

Speed correction factor (v_{ips}). Data based on tests of heavy-duty emissions versus average speed are unavailable. In the absence of these data, light-duty vehicle speed correction factors are recommended. The data presented in Tables 3.1.4-10 and Table 3.1.4-11 should be considered as interim heavy-duty vehicle speed correction factors until appropriate data become available.

Table 3.1.4-10. SPEED CORRECTION FACTORS FOR HEAVY-DUTY VEHICLES[a,b]

Location	Model year	$v_{ips} = e^{(A + BS + CS^2)}$						$v_{ips} = A + BS$	
		Hydrocarbons			Carbon monoxide			Nitrogen oxides	
		A	B	C	A	B	C	A	B
Low altitude	Pre-1970	0.953	-6.00×10^{-2}	5.81×10^{-4}	0.967	-6.07×10^{-2}	5.78×10^{-4}	0.808	0.980×10^{-2}
	1970-1972	1.070	-6.63×10^{-2}	5.98×10^{-4}	1.047	-6.52×10^{-2}	6.01×10^{-4}	0.888	0.569×10^{-2}
High altitude	Pre-1970	0.883	-5.58×10^{-2}	5.52×10^{-4}	0.721	-4.57×10^{-2}	4.56×10^{-4}	0.602	2.027×10^{-2}
	1970-1972	0.722	-4.63×10^{-2}	4.80×10^{-4}	0.662	-4.23×10^{-2}	4.33×10^{-4}	0.642	1.835×10^{-2}

[a] Reference 5. Equations should not be extended beyond the range of data (15 to 45 mi/hr). These data are from tests of light-duty vehicles and are assumed applicable to heavy-duty vehicles.

[b] Speed (s) is in miles per hour (1 mi/hr = 1.61 km/hr).

Table 3.1.4-11. LOW AVERAGE SPEED CORRECTION FACTORS FOR HEAVY-DUTY VEHICLES[a]

Location	Model year	Carbon monoxide		Hydrocarbons		Nitrogen oxides	
		5 mi/hr (8 km/hr)	10 mi/hr (16 km/hr)	5 mi/hr (8 km/hr)	10 mi/hr (16 km/hr)	5 mi/hr (8 km/hr)	10 mi/hr) (16 km/hr)
Low altitude	Pre-1970	2.72	1.57	2.50	1.45	1.08	1.03
	1970-1972	3.06	1.75	2.96	1.66	1.04	1.00
High altitude	Pre-1970	2.29	1.48	2.34	1.37	1.33	1.20
	1970-1972	2.43	1.54	2.10	1.27	1.22	1.18

[a] Driving patterns developed from CAPE-21 vehicle operation data (Reference 6) were input to the modal emission analysis model (see section 3.1.2.3). The results predicted by the model (emissions at 5 and 10 mi/hr; 8 and 16 km/hr) were divided by FTP emission factors for hot operation to obtain the above results. The above data represent the best currently available information for light-duty vehicles. These data are assumed applicable to heavy-duty vehicles given the lack of better information.

For an explanation of the derivation of these factors, see section 3.1.4.2.1.

In addition to exhaust emission factors, the calculation of evaporative and crankcase hydrocarbon emissions are determined using:

$$f_n = \sum_{i=n-12}^{n} h_i m_{in} \qquad (3.1.4\text{-}5)$$

where: f_n = The combined evaporative and crankcase hydrocarbon emission factor for calendar year (n)

h_i = The combined evaporative and crankcase hydrocarbon emission rate for the i^{th} model year. Emission factors for this source are reported in Table 3.1.4-12.

m_{in} = The weighted annual travel of the i^{th} model year vehicle during calendar year (n)

Table 3.1.4-12. CRANKCASE AND EVAPORATIVE HYDROCARBON EMISSION FACTORS FOR HEAVY-DUTY, GASOLINE-POWERED VEHICLES
EMISSION FACTOR RATING: B

Location	Model years	Crankcase hydrocarbon[a]		Evaporative hydrocarbons[b]	
		g/mi	g/km	g/mi	g/km
All areas except high altitude and California	Pre-1968	5.7	3.5	5.8	3.6
	1968-1972	0.0	0.0	5.8	3.6
California only	Pre-1964	5.7	3.5	5.8	3.6
	1964-1972	0.0	0.0	5.8	3.6
High altitude	Pre-1968	5.7	3.5	7.4	4.6
	1968-1972	0.0	0.0	7.4	4.6

[a] Crankcase factors are from Reference 12.

[b] References 1, 21, and 22 were used to estimate evaporative emission factors for heavy-duty vehicles. Equation 3.1.2-6 was used to calculate g/mi (g/km) values. (Evaporative emission factor = g + kd). The heavy-duty vehicle diurnal evaporative emissions (g) were assumed to be three times the light-duty vehicle value to account for the larger size fuel tanks used on heavy-duty vehicles. Nine trips per day (d = number of trips per day) from Reference 6 were used in conjunction with the light-duty vehicle hot soak emissions (k) to yield a total evaporative emission rate in grams per day. This value was divided by 36.2 mi/day (58.3 km/day) from Reference 7 to obtain the per mile (per kilometer) rate.

3.1.4.3.2 Sulfur oxide and particulate emissions – Sulfur oxide and particulate emission factors for all model year heavy-duty vehicles are presented in Table 3.1.4-13. Sulfur oxides factors are based on fuel sulfur content and fuel consumption. Tire-wear particulate factors are based on automobile test results – a premise necessary because of the lack of data. Truck tire wear is likely to result in greater particulate emissions than automobiles because of larger tires, heavier loads on tires, and more tires per vehicle. Although the factors presented in Table 3.1.4-13 can be adjusted for the number of tires per vehicle, adjustments cannot be made to account for the other differences.

Table 3.1.4-13. PARTICULATE AND SULFUR OXIDES EMISSION FACTORS FOR HEAVY-DUTY, GASOLINE-POWERED VEHICLES
EMISSION FACTOR RATING: B

Pollutant	Emissions	
	g/mi	g/km
Particulate		
Exhaust[a]	0.91	0.56
Tire wear[b]	0.20T	0.12T
Sulfur oxides[c] (SO_x as SO_2)	0.36	0.22

[a] Calculated from the Reference 13 value of 12 lb/10^3 gal (1.46 g/liter) gasoline. A 6.0 mi/gal (2.6 km/liter) value from Reference 23 was used to convert to a per kilometer (per mile) emission factor.

[b] Reference 14. The data from this reference are for passenger cars. In the absence of specific data for heavy-duty vehicles, they are assumed to be representative of truck-tire-wear particulate. An adjustment is made for trucks with more than four tires. T equals the number of tires divided by four.

[c] Based on an average fuel consumption of 6.0 mi/gal (2.6 km/liter) from Reference 23, on a 0.04 percent sulfur content from Reference 16 and 17, and on a density of 6.1 lb/gal (0.73 kg/liter) from References 16 and 17.

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3.1.5 Heavy-Duty, Diesel-Powered Vehicles

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3.1.5.1 General[1,2] – On the highway, heavy-duty diesel engines are primarily used in trucks and buses. Diesel engines in any application demonstrate operating principles that are significantly different from those of the gasoline engine.

3.1.5.2 Emissions – Diesel trucks and buses emit pollutants from the same sources as gasoline-powered vehicles: exhaust, crankcase blow-by, and fuel evaporation. Blow-by is practically eliminated in the diesel, however, because only air is in the cylinder during the compression stroke. The low volatility of diesel fuel along with the use of closed injection systems essentially eliminates evaporation losses in diesel systems.

Exhaust emissions from diesel engines have the same general characteristics of auto exhausts. Concentrations of some of the pollutants, however, may vary considerably. Emissions of sulfur dioxide are a direct function of the fuel composition. Thus, because of the higher average sulfur content of diesel fuel (0.20 percent S) as compared with gasoline (0.035 percent S), sulfur dioxide emissions are relatively higher from diesel exhausts.[3,4]

Because diesel engines allow more complete combustion and use less volatile fuels than spark-ignited engines, their hydrocarbon and carbon monoxide emissions are relatively low. Because hydrocarbons in diesel exhaust represent largely unburned diesel fuel, their emissions are related to the volume of fuel sprayed into the combustion chamber. Both the high temperature and the large excesses of oxygen involved in diesel combustion are conducive to high nitrogen oxide emission, however.[6]

Particulates from diesel exhaust are in two major forms – black smoke and white smoke. White smoke is emitted when the fuel droplets are kept cool in an environment abundant in oxygen (cold starts). Black smoke is emitted when the fuel droplets are subjected to high temperatures in an environment lacking in oxygen (road conditions).

Emissions from heavy-duty diesel vehicles during a calendar year (n) and for a pollutant (p) can be approximately calculated using:

$$e_{nps} = \sum_{i=n-12}^{n} c_{ipn} v_{ips} \qquad (3.1.5\text{-}1)$$

where: e_{nps} = Composite emission factor in g/mi (g/km) for calendar year (n), pollutant (p), and average speed (s)

c_{ipn} = The emission rate in g/mi (g/km) for the i^{th} model year vehicles in calendar year (n) over a transient urban driving schedule with an average speed of approximately 18 mi/hr (29 km/hr)

v_{ips} = The speed correction factor for the i^{th} model year heavy-duty diesel vehicles for pollutant (p) and average speed (s)

Values for c_{ipn} are given in Table 3.1.5-1. These emission factors are based on tests of vehicles on-the-road over the San Antonio Road Route (SARR). The SARR, located in San Antonio, Texas, is 7.24 miles long and includes freeway, arterial, and local/collector highway segments.[7] A constant volume sampler is carried on board

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each test vehicle for collection of a proportional part of the vehicle's exhaust. This sample is later analyzed to yield mass emission rates. Because the SARR is an actual road route, the average speed varies depending on traffic conditions at the time of the test. The average speed, however, tends to be around 18 mi/hr (29 km/hr), with about 20 percent of the time spent at idle. The test procedure emission factor is composed entirely of warmed-up vehicle operation. Based on a preliminary analysis of vehicle operation data, heavy-duty vehicles operate primarily (about 95 percent) in a warmed-up condition.

Table 3.1.5-1. EMISSION FACTORS FOR HEAVY-DUTY, DIESEL-POWERED VEHICLES (ALL PRE-1973 MODEL YEARS) FOR CALENDAR YEAR 1972
EMISSION FACTOR RATING: B

Pollutant	Truck emissions[a]		City bus emissions[b]	
	g/mi	g/km	g/mi	g/km
Particulate[c]	1.3	0.81	1.3	0.81
Sulfur oxides[c,d] (SO_x as SO_2)	2.8	1.7	2.8	1.7
Carbon monoxide	28.7	17.8	21.3	13.2
Hydrocarbons	4.6	2.9	4.0	2.5
Nitrogen oxides (NO_x as NO_2)	20.9	13.0	21.5	13.4
Aldehydes[c] (as HCHO)	0.3	0.2	0.3	0.2
Organic acids[c]	0.3	0.2	0.3	0.2

[a] Truck emissions are based on over-the-road sampling of diesel trucks by Reference 7. Sampling took place on the San Antonio (Texas) Road Route (SARR), which is 7.24 miles (11.7 kilometers) long and includes freeway, arterial, and local/collector highway segments. Vehicles average about 18 mi/hr (29 km/hr) over this road route.

[b] Bus emission factors are also based on the SARR. 13-Mode emission data from Reference 6 were converted to SARR values using cycle-to-cycle conversion factors from Reference 8.

[c] Reference 6. Tire wear particulate not included in above particulate emission factors. See tire wear particulate, heavy-duty gasoline section.

[d] Data based on assumed fuel sulfur content of 0.20 percent. A fuel economy of 4.6 mi/gal (2.0 km/liter) was used from Reference 9.

The speed correction factor, v_{ips}, can be computed using data in Table 3.1.5-2. Table 3.1.5-2 gives heavy-duty diesel HC, CO, and NO_x emission factors in grams per minute for the idle mode, an urban transient mode with average speed of 18 mi/hr (29 km/hr), and an over-the-road mode with an average speed of approximately 60 mi/hr (97 km/hr). For average speeds less than 18 mi/hr (29 km/hr), the correction factor is:

$$v_{ips} = \frac{\text{Urban} + \left(\frac{18}{S} - 1\right) \text{Idle}}{\text{Urban}} \tag{3.1.5-2}$$

where: s is the average speed of interest (in mi/hr), and the urban and idle values (in g/min) are obtained from Table 3.1.5-2. For average speeds above 18 mi/hr (29 km/hr), the correction factor is:

$$v_{ips} = \frac{\frac{18}{42S} \left[(60\text{-}S) \text{ Urban} + (S\text{-}18) \text{ Over the Road}\right]}{\text{Urban}} \tag{3.1.5-3}$$

Where: S is the average speed (in mi/hr) of interest. Urban and over-the-road values (in g/min) are obtained from Table 3.1.5-2. Emission factors for heavy-duty diesel vehicles assume all operation to be under warmed-up vehicle conditions. Temperature correction factors, therefore, are not included because ambient temperature has minimal effects on warmed-up operation.

Table 3.1.5-2. EMISSION FACTORS FOR HEAVY-DUTY DIESEL VEHICLES UNDER DIFFERENT OPERATING CONDITIONS

EMISSION FACTOR RATING: B

Pollutant	Emission factors,[a] g/min		
	Idle	Urban [18 mi/hr (29 km/hr)]	Over-the-road [60 mi/hr (97 km/hr)]
Carbon monoxide	0.64	8.61	5.40
Hydrocarbons	0.32	1.38	2.25
Nitrogen oxides (NO_x as NO_2)	1.03	6.27	28.3

[a] Reference 7. Computed from data contained in the reference.

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3.1.6 Gaseous-Fueled Vehicles

by David S. Kircher

3.1.6.1 General – Conversion of vehicles to gaseous fuels has been practiced for many years. In the past the principal motivation for the conversion has been the economic advantage of gaseous fuels over gasoline rather than lower air pollutant emission levels that result from their use. Recently, however, conversions have been made for air pollution control as well as for lower operating cost. Liquified petroleum gas (LPG), the most common form of gaseous fuel for vehicles, is currently used to power approximately 300,000 vehicles in the United States. Natural gas, in the form of compressed natural gas (CNG) or liquified natural gas (LNG), is being used nationally to power about 4,000 vehicles.[1] Of the two natural gas fuels, CNG is the most common. Natural gas conversions are usually dual fuel systems that permit operation on either gaseous fuel (CNG or LNG) or gasoline.

3.1.6.2 Emissions – Tables 3.1.6-1 and 3.1.6-2 contain emission factors for light- and heavy-duty vehicles converted for either gaseous fuel or dual fuel operation. The test data used to determine the average light duty emission factors were based on both the 1972 Federal test procedure and the earlier seven-mode method.[7,8] These test data were converted to the current Federal test procedure[9] using conversion factors determined empirically.[10,11] This conversion was necessary to make the emission factors for these vehicles consistent with emission factors reported in previous sections of this chapter.

Heavy-duty vehicle emission factors (Table 3.1.6-2) are based on tests of vehicles on an experimental dynamometer test cycle[6] and on the Federal test procedure. Emissions data for heavy-duty vehicles are limited to tests of only a few vehicles. For this reason the factors listed in table 3.1.6-2 are only approximate indicators of emissions from these vehicles.

Emission data on gaseous-powered vehicles are limited to dynamometer test results. Deterioration factors and speed correction factors are not available. The data contained in the tables, therefore, are emission factors for in-use vehicles at various mileages rather than emission rates (as defined in section 3.1.2).

Emission factors for a particular population of gaseous-fueled vehicles can be determined using the relationship:

$$e_{npwc} = \sum_{i=n-12}^{n+1} c_i f_i \qquad (1)$$

where: e_{npwc} = Emission factor is grams per mile (or g/km) for calendar year (n), pollutant (p), vehicle weight (w) (light- or heavy-duty), and conversion fuel system (c) (e.g. LPG)

c_i = The test cycle emission factor (Tables 3.1.6-1 and 3.1.6-2) for pollutant (p) for the ith model year vehicles

f_i = The fraction of total miles driven by a population of gaseous-fueled vehicles that are driven by the ith model year vehicles

Carbon monoxide, hydrocarbon, and nitrogen oxides emission factors are listed in the tables. Particulates and sulfur oxides are not listed because of the lack of test data. Because stationary external combustion of gaseous fuel results in extremely low particulate and sulfur oxides, it is reasonable to assume that the emissions of these pollutants from gaseous-fueled vehicles are negligible.

Table 3.1.6-1. EMISSION FACTORS BY MODEL YEAR FOR LIGHT-DUTY VEHICLES USING LPG, LPG/DUAL FUEL, OR CNG/DUAL FUEL[a]
EMISSION FACTOR RATING: B

Fuel and model year	Carbon monoxide		Exhaust hydrocarbons		Nitrogen oxides (NO_x as NO_2)	
	g/mi	g/km	g/mi	g/km	g/mi	g/km
LPG						
Pre-1970[b]	11	6.8	1.8	1.1	3.2	2.0
1970 through 1972[c]	3.4	2.1	0.67	0.42	2.8	1.7
LPG/Dual fuel[d]						
Pre-1973	7.8	4.8	2.4	1.5	3.4	2.1
CNG/Dual fuel[e]						
Pre-1973	9.2	5.7	1.5	0.93	2.8	1.7

[a] References 1 through 5.

[b] Emission factors are based on tests of 1968 and 1969 model year vehicles. Sufficient data for earlier models are not available.

[c] Based on tests of 1970 model year vehicles. No attempt was made to predict the emissions resulting from the conversion of post 1974 model year vehicles to gaseous fuels. It is likely that 1973 and 1974 model year vehicles converted to gaseous fuels will emit pollutant quantities similar to those emitted by 1972 vehicles with the possible exception of nitrogen oxides.

[d] The dual fuel system represents certain compromises in emission performance to allow the flexibility of operation on gaseous or liquid (gasoline) fuels. For this reason their emission factors are listed separately from vehicles using LPG only.

[e] Based on tests of 1968 and 1969 model year vehicles. It is likely that 1973 and 1974 model year vehicles will emit similar pollutant quantities to those listed with the possible exception of nitrogen oxides. No attempt was made to estimate 1975 and later model year gaseous-fueled-vehicle emissions.

Table 3.1.6-2. EMISSION FACTORS FOR HEAVY-DUTY VEHICLES USING LPG OR CNG/DUAL FUEL
EMISSION FACTOR RATING: C

Pollutant	Emissions (all model years)[a]			
	LPG[b,c]		CNG/dual fuel[d]	
	g/mi	g/km	g/mi	g/km
Carbon monoxide	4.2	2.6	7.5	4.6
Exhaust hydrocarbons	2.4	1.5	2.2	1.4
Nitrogen oxides (NO_x as NO_2)	2.8	1.7	5.8	3.6

[a] Test results are for 1959 through 1970 model years. These results are assumed to apply to all future heavy-duty vehicles based on present and future emission standards.

[b] References 2 and 4.

[c] LPG values for heavy-duty vehicles are based on a limited number of tests of vehicles tuned for low emissions. Vehicles converted to LPG solely for economic reasons gave much higher emission values. For example, eleven vehicles (1950 through 1963) tested in Reference 6 demonstrated average emissions of 160 g/mi (99 g/km) of carbon monoxide, 8.5 g/mi (5.3 g/km) of hydrocarbons, and 4.2 g/mil (2.6 g/km) of nitrogen oxides.

[d] Reference 5.

References for Section 3.1.6

1. Conversion of Motor Vehicles to Gaseous Fuel to Reduce Air Pollution. U.S. Environmental Protection Agency, Office of Air Programs. Washington, D.C. April 1972.
2. Fleming, R.D. et al. Propane as an Engine Fuel for Clean Air Requirements. J. Air Pol. Control Assoc. *22:*451-458. June 1972.
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3.1.7 Motorcycles

by David S. Kircher

3.1.7.1 General – Motorcycles, which are not, generally, considered an important source of air pollution, have become more popular and their numbers have been steadily increasing in the last few years. Sales grew at an annual rate of 20 percent from 1965 to 1971.[1] The majority of motorcycles are powered by either 2- or 4-stroke, air-cooled engines; however, water-cooled motorcycles and Wankel-powered motorcycles have recently been introduced. Until recently the predominant use of 4-stroke motorcycles was on-highway and the 2-stroke variety was off-highway. This difference in roles was primarily a reflection of significant weight and power variations between available 2- and 4-stroke vehicles. As light-weight 4-strokes and more powerful 2-strokes become available the relative number of motorcycles in each engine category may change. Currently the nationwide population of motorcycles is approximately 38 percent 2-stroke and 62 percent 4-stroke. Individual motorcycles travel, on the average, approximately 4000 miles per year.[1] These figures, along with registration statistics, enable the rough estimation of motorcycle miles by engine category and the computation of resulting emissions.

3.1.7.2 Emissions – The quantity of motorcycle emission data is rather limited in comparison with the data available on other highway vehicles. For instance, data on motorcycle average speed versus emission levels are not available. Average emission factors for motorcycles used on highways are reported in Table 3.1.7-1. These data, from several test vehicles, are based on the Federal light-duty vehicle test procedure.[2] The table illustrates differences in 2-stroke and 4-stroke engine emission rates. On a per mile basis, 2-stroke engines emit nearly five times more hydrocarbons than 4-stroke engines. Both engine categories emit somewhat similar quantities of carbon monoxide and both produce low levels of nitrogen oxides.

Table 3.1.7-1. EMISSION FACTORS FOR MOTORCYCLES[a] EMISSION FACTOR RATING: B

Pollutant	Emissions			
	2-stroke engine		4-stroke engine	
	g/mi	g/km	g/mi	g/km
Carbon monoxide	27	17	33	20
Hydrocarbons				
Exhaust	16	9.9	2.9	1.8
Crankcase[b]	–	–	0.60	0.37
Evaporative[c]	0.36	0.22	0.36	0.22
Nitrogen oxides (NO_x as NO_2)	0.12	0.075	0.24	0.15
Particulates	0.33	0.21	0.046	0.029
Sulfur oxides[d] (SO_2)	0.038	0.024	0.022	0.014
Aldehydes (RCHO as HCHO)	0.11	0.068	0.047	0.029

[a] Reference 1.

[b] Most 2-stroke engines use crankcase induction and produce no crankcase losses.

[c] Evaporative emissions were calculated assuming that carburetor losses were negligible. Diurnal breathing of the fuel tank (a function of fuel vapor pressure, vapor space in the tank, and diurnal temperature variation) was assumed to account for all the evaporative losses associated with motorcycles. The value presented is based on average vapor pressure, vapor space, and temperature variation.

[d] Calculated using a 0.043 percent sulfur content (by weight) for regular fuel used in 2-stroke engines and 0.022 percent sulfur content (by weight) for premium fuel used in 4-stroke engines.

References for Section 3.1.7

1. Hare, C.T. and K.J. Springer. Exhaust Emissions from Uncontrolled Vehicles and Related Equipment Using Internal Combustion Engines. Part III, Motorcycles. Final Report. Southwest Research Institute. San Antonio, Texas. Prepared for the Environmental Protection Agency, Research Triangle Park, N.C., under Contract Number EHS 70-108. March 1973.

2. Exhaust Emission Standards and Test Procedures. Federal Register. *36*(128):12652-12663, July 2, 1971.

3.2 OFF-HIGHWAY, MOBILE SOURCES

The off-highway category of internal combustion engines embraces a wide range of mobile and semimobile sources. Emission data are reported in this section on the following sources: aircraft; locomotives; vessels (inboard and outboard); and small general utility engines, such as those used in lawnmowers and minibikes. Other sources that fall into this category, but for which emission data are not currently available, include: snowmobiles, all-terrain vehicles, and farm and construction equipment. Data on these sources will be added to this chapter in future revisions.

3.2.1 Aircraft

by Charles C. Masser

3.2.1.1 General – Aircraft engines are of two major categories; reciprocating (piston) and gas turbine.

The basic element in the aircraft piston engine is the combustion chamber, or cylinder, in which mixtures of fuel and air are burned and from which energy is extracted through a piston and crank mechanism that drives a propeller. The majority of aircraft piston engines have two or more cylinders and are generally classified according to their cylinder arrangement – either "opposed" or radial." Opposed engines are installed in most light or utility aircraft; radial engines are used mainly in large transport aircraft.

The gas turbine engine in general consists of a compressor, a combustion chamber, and a turbine. Air entering the forward end of the engine is compressed and then heated by burning fuel in the combustion chamber. The major portion of the energy in the heated air stream is used for aircraft propulsion. Part of the energy is expended in driving the turbine, which in turn drives the compressor. Turbofan and turboshaft engines use energy from the turbine for propulsion; turbojet engines use only the expanding exhaust stream for propulsion.

The aircraft classification system used is listed in Table 3.2.1-1. Both turbine aircraft and piston engine aircraft have been further divided into sub-classes depending on the size of the aircraft and the most commonly used engine for that class. Jumbo jets normally have approximately 40,000 pounds maximum thrust per engine, and medium-range jets have about 14,000 pounds maximum thrust per engine. For piston engines, this division is more pronounced. The large transport piston engines are in the 500 to 3,000 horsepower range, whereas the small piston engines develop less than 500 horsepower.

Table 3.2.1-1. AIRCRAFT CLASSIFICATION

Aircraft class	Representative aircraft	Engines per aircraft	Engine commonly used
Jumbo jet	Boeing 747 Lockheed L-1011 McDonald Douglas DC-10	4 3 3	Pratt & Whitney JT-9D
Long-range jet	Boeing 707 McDonald Douglas DC-8	4 4	Pratt & Whitney JT-3D
Medium-range jet	Boeing 727 Boeing 737 McDonald Douglas DC-9	3 2 2	Pratt & Whitney JT-8D
Air carrier turboprop	Convair 580 Electra L-188 Fairchild Hiller FH-227	2 4 2	Allison 501-D13
Business jet	Gates Learjet Lockheed Jetstar	2 4	General Electric CJ610 Pratt & Whitney JT-12A
General aviation turboprop	–	–	Pratt & Whitney PT-6A
General aviation piston	Cessna 210 Piper 32-300	1 1	Teledyne-Continental 0-200 Lycoming 0-320
Piston transport	Douglas DC-6	4	Pratt & Whitney R-2800
Helicopter	Sikorsky S-61 Vertol 107	2 2	General Electric CT-58
Military transport			Allison T56A7
Military jet			General Electric J-79 Continental J-69
Military piston			Curtiss-Wright R-1820

3.2.1.2 Landing and Takeoff Cycle – A landing-takeoff (LTO) cycle includes all normal operation modes performed by an aircraft between the time it descends through an altitude of 3,500 feet (1,100 meters) on its approach and the time it subsequently reaches the 3,500 foot (1,100 meters) altitude after take. It should be made clear that the term "operation" used by the Federal Aviation Administration to describe either a landing or a takeoff is not the same as the LTO cycle. Two operations are involved in one LTO cycle. The LTO cycle incorporates the ground operations of idle, taxi, landing run, and takeoff run and the flight operations of takeoff and climbout to 3,500 feet (1,100 meters) and approach from 3,500 feet (1,100 meters) to touchdown

Each class of aircraft has its own typical LTO cycle. In order to determine emissions, the LTO cycle is separated into five distinct modes: (1) taxi-idle, (2) takeoff, (3) climbout, (4) approach and landing, and (5) taxi-idle. Each of these modes has its share of time in the LTO cycle. Table 3.2.1-2 shows typical operating time in each mode for the various types of aircraft classes during periods of heavy activity at a large metropolitan airport. Emissions factors for the complete LTO cycle presented in Table 3.2.1-3 were determined using the typical times shown in Table 3.2.1-2.

Table 3.2.1-2. TYPICAL TIME IN MODE FOR LANDING TAKEOFF CYCLE AT A METROPOLITAN AIRPORT[a]

Aircraft	Time in mode, minutes				
	Taxi-idle	Takeoff	Climbout	Approach	Taxi-idle
Jumbo jet	19.00	0.70	2.20	4.00	7.00
Long range jet	19.00	0.70	2.20	4.00	7.00
Medium range jet	19.00	0.70	2.20	4.00	7.00
Air carrier turboprop	19.00	0.50	2.50	4.50	7.00
Business jet	6.50	0.40	0.50	1.60	6.50
General aviation turboprop	19.00	0.50	2.50	4.50	7.00
General aviation piston	12.00	0.30	4.98	6.00	4.00
Piston transport	6.50	0.60	5.00	4.60	6.50
Helicopter	3.50	0	6.50	6.50	3.50
Military transport	19.00	0.50	2.50	4.50	7.00
Military jet	6.50	0.40	0.50	1.60	6.50
Military piston	6.50	0.60	5.00	4.60	6.50

[a] References 1 and 2.

Table 3.2.1-3. EMISSION FACTORS PER AIRCRAFT LANDING-TAKEOFF CYCLE[a,b]

(lb/engine and kg/engine)

EMISSION FACTOR RATING: B

Aircarft	Solid particulates[a]		Sulfur oxides[d]		Carbon monoxide[e]		Hydrocarbons[e]		Nitrogen oxides[d] (NO_x as NO_2)	
	lb	kg	lb	kg	lb	kg	lb	kg	lb	kg
Jumbo jet	1.30	0.59	1.82	0.83	46.8	21.2	12.2	5.5	31.4	14.2
Long range jet	1.21	0.55	1.56	0.71	47.4	21.5	41.2	18.7	7.9	3.6
Medium range jet	0.41	0.19	1.01	0.46	17.0	7.71	4.9	2.2	10.2	4.6
Air carrier turboprop	1.1	0.49	0.40	0.18	6.6	3.0	2.9	1.3	2.5	1.1
Business jet	0.11	0.05	0.37	0.17	15.8	7.17	3.6	1.6	1.6	0.73
General aviation turboprop	0.20	0.09	0.18	0.08	3.1	1.4	1.1	0.5	1.2	0.54
General aviation piston	0.02	0.01	0.014	0.006	12.2	5.5	0.40	0.18	0.047	0.021
Piston transport	0.56	0.25	0.28	0.13	304.0	138.0	40.7	18.5	0.40	0.18
Helicopter	0.25	0.11	0.18	0.08	5.7	2.6	0.52	0.24	0.57	0.26
Military transport	1.1	0.49	0.41	0.19	5.7	2.6	2.7	1.2	2.2	1.0
Military jet	0.31	0.14	0.76	0.35	15.1	6.85	9.93	4.5	3.29	1.49
Military piston[f]	0.28	0.13	0.14	0.04	152.0	69.0	20.4	9.3	0.20	0.09

[a] References 1 through 5.

[b] Emission factors based on typical times in mode shown in Table 3.2.1-2.

[c] References 1 and 5.

[d] Based on 0.05 percent sulfur content fuel.

[e] References 1, 2, and 4.

[f] Engine emissions based on Pratt & Whitney R-2800 engine scaled down two times.

3.2.1.3 Modal Emission Factors – In Table 3.2.1-4 a set of modal emission factors by engine type are given for carbon monoxide, total hydrocarbons, nitrogen oxides, and solid particulates along with the fuel flow rate per engine for each LTO mode. With this data and knowledge of the time-in-mode, it is possible to construct any LTO cycle or mode and calculate a more accurate estimate of emissions for the situation that exists at a specific airport. This capability is especially important for estimating emissions during the taxi-idle mode when large amounts of carbon monoxide and hydrocarbons are emitted. At smaller commercial airports the taxi-idle time will be less than at the larger, more congested airports.

Table 3.2.1-4. MODAL EMISSION FACTORS[a]
EMISSION FACTOR RATING: B

Engine and mode	Fuel rate		Carbon monoxide		Hydrocarbons		Nitrogen oxides (NO_x as NO_2)		Solid particulates	
	lb/hr	kg/hr	lb/hr	kg/hr	lb/hr	kg/hr	lb/hr	kg/hr	lb/hr	kg/hr
Pratt & Whitney JT-9D (Jumbo jet)										
Taxi-idle	1,738	788	102.0	46.3	27.3	12.4	6.06	2.75	2.2	1.0
Takeoff	17,052	7,735	8.29	3.76	2.95	1.34	720.0	327.0	3.75	1.7
Climbout	14,317	6,494	11.7	5.31	2.65	1.20	459.0	208.0	4.0	1.8
Approach	5,204	2,361	32.6	14.8	3.00	1.36	54.1	24.5	2.3	1.0
General Electric CF6 (Jumbo jet)										
Taxi-idle	1,030	467	51.7	23.5	15.4	7.0	3.6	1.63	0.04	0.02
Takeoff	13,449	6,100	6.7	3.04	1.3	0.59	540.0	245.0	0.54	0.24
Climbout[b]	11,400	5,171	6.6	2.99	1.3	0.59	333.0	151.0	0.54	0.24
Approach	6,204	2,814	18.6	8.44	1.9	0.86	173.0	78.5	0.44	0.20
Pratt & Whitney JT-3D (Long range jet)										
Taxi-idle	872	396	109.0	49.4	98.6	44.7	1.43	0.649	0.45	0.20
Takeoff	10,835	4,915	12.3	5.60	4.65	2.11	148.0	67.1	8.25	3.7
Climbout	8,956	4,062	15.3	6.94	4.92	2.23	96.2	43.6	8.5	3.9
Approach	4,138	1,877	39.7	18.0	7.84	3.56	21.8	9.89	8.0	3.6
Pratt & Whitney JT-3C (Long range jet)										
Taxi-idle	1,198	543	92.6	42.0	92.2	41.8	2.49	1.13	0.40	0.18
Takeoff	10,183	4,619	9.04	4.10	0.855	0.388	119.0	54.0	6.50	2.9
Climbout	8,509	3,860	16.0	7.26	0.893	0.405	84.7	38.4	6.25	2.8
Approach	4,115	1,867	49.0	22.2	8.26	3.75	23.2	10.5	3.25	1.5
Pratt & Whitney JT-4A (Long range jet)										
Taxi-idle	1,389	630	62.8	28.5	64.8	29.4	2.71	1.23	1.2	0.54
Takeoff	15,511	7,036	18.8	8.53	0.674	0.306	236.0	107.0	21.0	9.5
Climbout	13,066	5,927	18.3	8.30	1.27	0.576	155.0	70.3	20.0	9.1
Approach	5,994	2,719	26.3	11.9	3.83	1.74	35.9	16.3	6.0	2.7

Table 3.2.1-4 (continued). MODAL EMISSION FACTORS[a]
EMISSION FACTOR RATING: B

Engine and mode	Fuel rate		Carbon monoxide		Hydrocarbons		Nitrogen oxides (NO_x as NO_2)		Solid particulates	
	lb/hr	kg/hr	lb/hr	kg/hr	lb/hr	Kg/hr	lb/hr	kg/hr	lb/hr	kg/hr
General Electric CJ805 (Long range jet)										
Taxi-idle	1,001	454	63.8	28.9	27.3	12.4	1.57	0.712	1.3	0.59
Takeoff	9,960	4,518	29.1	13.2	0.556	0.252	111.0	50.3	15.0	6.8
Climbout	8,290	3,760	28.9	13.1	0.583	0.264	74.0	33.6	15.0	6.8
Approach	3,777	1,713	42.8	19.4	2.43	1.10	17.8	8.07	5.0	2.3
Pratt & Whitney JT-8D[c] (Med. range jet)										
Taxi-idle	959	435	33.4	15.2	6.99	3.71	2.91	1.32	0.36	0.16
Takeoff	8,755	3,971	7.49	3.40	0.778	0.353	198.0	89.8	3.7	1.7
Climbout	7,337	3,328	8.89	4.03	0.921	0.418	131.0	59.4	2.6	1.2
Approach	3,409	1,546	18.2	8.26	1.75	0.794	30.9	14.0	1.5	0.68
Rolls Royce Sprey MK511 (Med. range jet)										
Taxi-idle	662	300	60.2	27.3	66.1	30.0	0.849	0.385	0.17	0.077
Takeoff	7,625	3,459	14.2	6.44	Neg	Neg	153.0	69.4	16.0	7.3
Climbout	6,355	2,883	15.3	6.94	0.242	0.110	115.0	52.2	10.0	4.5
Approach	3,052	1,384	39.1	17.7	4.22	1.91	30.4	13.8	1.5	0.68
Allison T56-A15 (Air carrier turboprop; mil. transport)										
Taxi-idle	493	224	8.74	3.96	7.39	3.35	1.23	0.560	1.6	0.73
Takeoff	2,393	1,085	3.77	1.71	0.440	0.200	27.9	12.7	3.7	1.7
Climbout	2,188	992	3.40	1.54	0.399	0.181	22.2	10.1	3.0	1.4
Approach	1,146	520	3.49	1.58	0.326	0.148	7.32	3.32	3.0	1.4
Allison T56-A7 (Air carrier turboprop; mil. transport)										
Taxi-idle	548	249	15.3	6.94	6.47	2.93	2.16	0.980	1.6	0.73
Takeoff	2,079	943	2.15	0.975	0.430	0.195	22.9	10.4	3.7	1.7
Climbout	1,908	865	3.01	1.37	0.476	0.216	21.2	9.62	3.0	1.4
Approach	1,053	478	3.67	1.66	0.517	0.235	7.78	3.53	3.0	1.4

Table 3.2.1-4 (continued). MODAL EMISSION FACTORS[a]
EMISSION FACTOR RATING: B

Engine and mode	Fuel rate		Carbon monoxide		Hydrocarbons		Nitrogen oxides (NO_x as NO_2)		Solid particulates	
	lb/hr	kg/hr	lb/hr	kg/hr	lb/hr	kg/hr	lb/hr	kg/hr	lb/hr	kg/hr
Airesearch TPE-331[d] (Gen. aviation turboprop)										
Taxi-idle	146	66.2	3.53	1.60	0.879	0.399	0.955	0.433	0.3	0.14
Takeoff	365	166.0	0.393	0.178	0.055	0.025	3.64	1.65	0.8	0.36
Climbout	339	154.0	0.568	0.258	0.053	0.024	3.31	1.50	0.6	0.27
Approach	206	93.4	2.58	1.17	0.240	0.109	1.69	0.767	0.6	0.27
Teledyne/Continental 0-200 (Gen. aviation piston)										
Taxi-idle	7.68	3.48	7.52	3.41	0.214	0.097	0.009	0.004	NA[e]	NA
Takeoff	48.4	22.0	54.6	24.8	0.720	0.327	0.259	0.117	NA	NA
Climbout	48.4	22.0	54.6	24.8	0.720	0.327	0.259	0.117	NA	NA
Approach	21.3	9.66	23.8	10.8	0.380	0.172	0.052	0.024	NA	NA
Lycoming 0-320 (Gen. aviation piston)										
Taxi-idle	13.0	5.90	11.1	5.03	0.355	0.161	0.013	0.006	NA	NA
Takeoff	65.7	29.8	70.9	32.2	1.49	0.676	0.214	0.097	NA	NA
Climbout	63.5	28.8	65.8	29.8	1.31	0.594	0.375	0.170	NA	NA
Approach	23.1	10.5	24.3	11.0	0.496	0.225	0.051	0.023	NA	NA

[a] References 4 and 5.

[b] Estimated and/or calculated.

[c] "Diluted smokeless" JT-8D. All air carriers scheduled for conversion of JT-8D engines to smokeless by January 1973.

[d] Similar to the PT-6A engine.

[e] NA—Not available.

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3. Assessment of Aircraft Emission Control Technology. Northern Research and Engineering Corporation, Cambridge, Mass. Prepared for the Environmental Protection Agency, Research Triangle Park, N.C., under Contract Number 68-04-0011. September 1971.

4. Analysis of Aircraft Exhaust Emission Measurements. Cornell Aeronautical Laboratory Inc. Buffalo, N.Y. Prepared for the Environmental Protection Agency, Research Triangle Park, N.C., under Contract Number 68-04-0040. October 1971.

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3.2.2 Locomotives

by David S. Kircher

3.2.2.1 General – Railroad locomotives generally follow one of two use patterns: railyard switching or road-haul service. Locomotives can be classified on the basis of engine configuration and use pattern into five categories: 2-stroke switch locomotive (supercharged), 4-stroke switch locomotive, 2-stroke road service locomotive (supercharged), 2-stroke road service locomotive (turbocharged), and 4-stroke road service locomotive.

The engine duty cycle of locomotives is much simpler than many other applications involving diesel internal combustion engines because locomotives usually have only eight throttle positions in addition to idle and dynamic brake. Emission testing is made easier and the results are probably quite accurate because of the simplicity of the locomotive duty cycle.

3.2.2.2 Emissions – Emissions from railroad locomotives are presented two ways in this section. Table 3.2.2-1 contains average factors based on the nationwide locomotive population breakdown by category. Table 3.2.2-2 gives emission factors by locomotive category on the basis of fuel consumption and on the basis of work output (horsepower hour).

The calculation of emissions using fuel-based emission factors is straightforward. Emissions are simply the product of the fuel usage and the emission factor. In order to apply the work output emission factor, however, an

Table 3.2.2-1. AVERAGE LOCOMOTIVE EMISSION FACTORS BASED ON NATIONWIDE STATISTICS[a]

Pollutant	Average emissions[b] lb/10^3 gal	Average emissions[b] kg/10^3 liter
Particulates[c]	25	3.0
Sulfur oxides[d] (SO_x as SO_2)	57	6.8
Carbon monoxide	130	16
Hydrocarbons	94	11
Nitrogen oxides (NO_x as NO_2)	370	44
Aldehydes (as HCHO)	5.5	0.66
Organic acids[c]	7	0.84

[a] Reference 1.

[b] Based on emission data contained in Table 3.2.2-2 and the breakdown of locomotive use by engine category in the United States in Reference 1.

[c] Data based on highway diesel data from Reference 2. No actual locomotive particulate test data are available.

[d] Based on a fuel sulfur content of 0.4 percent from Reference 3.

Table 3.2.2-2. EMISSION FACTORS BY LOCOMOTIVE ENGINE CATEGORY[a]
EMISSION FACTOR RATING: B

Pollutant	Engine category				
	2-Stroke supercharged switch	4-Stroke switch	2-Stroke supercharged road	2-Stroke turbocharged road	4-Stroke road
Carbon monoxide					
lb/10^3 gal	84	380	66	160	180
kg/10^3 liter	10	46	7.9	19	22
g/hphr	3.9	13	1.8	4.0	4.1
g/metric hphr	3.9	13	1.8	4.0	4.1
Hydrocarbon					
lb/10^3 gal	190	146	148	28	99
kg/10^3 liter	23	17	18	3.4	12
g/hphr	8.9	5.0	4.0	0.70	2.2
g/metric hphr	8.9	5.0	4.0	0.70	2.2
Nitrogen oxides (NO_x as NO_2)					
lb/10^3 gal	250	490	350	330	470
kg/10^3 liter	30	59	42	40	56
g/hphr	11	17	9.4	8.2	10
g/metric hphr	11	17	9.4	8.2	10

[a] Use average factors (Table 3.2.2-1) for pollutants not listed in this table.

additional calculation is necessary. Horsepower hours can be obtained using the following equation:

$$w = l p h$$

where: w = Work output (horsepower hour)

l = Load factor (average power produced during operation divided by available power)

p = Available horsepower

h = Hours of usage at load factor (l)

After the work output has been determined, emissions are simply the product of the work output and the emission factor. An approximate load factor for a line-haul locomotive (road service) is 0.4; a typical switch engine load factor is approximately 0.06.[1]

References for Section 3.2.2

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3.2.3 Inboard-Powered Vessels

Revised by David S. Kircher

3.2.3.1 General – Vessels classified on the basis of use will generally fall into one of three categories: commercial, pleasure, or military. Although usage and population data on vessels are, as a rule, relatively scarce, information on commercial and military vessels is more readily available than data on pleasure craft. Information on military vessels is available in several study reports,[1-5] but data on pleasure craft are limited to sales-related facts and figures.[6-10]

Commercial vessel population and usage data have been further subdivided by a number of industrial and governmental researchers into waterway classifications[11-16] (for example, Great Lakes vessels, river vessels, and coastal vessels). The vessels operating in each of these waterway classes have similar characteristics such as size, weight, speed, commodities transported, engine design (external or internal combustion), fuel used, and distance traveled. The wide variation between classes, however, necessitates the separate assessment of each of the waterway classes with respect to air pollution.

Information on military vessels is available from both the U.S. Navy and the U.S. Coast Guard as a result of studies completed recently. The U.S. Navy has released several reports that summarize its air pollution assessment work.[3-5] Emission data have been collected in addition to vessel population and usage information. Extensive study of the air pollutant emissions from U.S. Coast Guard watercraft has been completed by the U.S. Department of Transportation. The results of this study are summarized in two reports.[1-2] The first report takes an in-depth look at population/usage of Coast Guard vessels. The second report, dealing with emission test results, forms the basis for the emission factors presented in this section for Coast Guard vessels as well as for non-military diesel vessels.

Although a large portion of the pleasure craft in the U.S. are powered by gasoline outboard motors (see section 3.2.4 of this document), there are numerous larger pleasure craft that use inboard power either with or without "out-drive" (an outboard-like lower unit). Vessels falling into the inboard pleasure craft category utilize either Otto cycle (gasoline) or diesel cycle internal combustion engines. Engine horsepower varies appreciably from the small "auxiliary" engine used in sailboats to the larger diesels used in yachts.

3.2.3.2 Emissions

Commercial vessels. Commercial vessels may emit air pollutants under two major modes of operation: underway and at dockside (auxiliary power).

Emissions underway are influenced by a great variety of factors including power source (steam or diesel), engine size (in kilowatts or horsepower), fuel used (coal, residual oil, or diesel oil), and operating speed and load. Commercial vessels operating within or near the geographic boundaries of the United States fall into one of the three categories of use discussed above (Great Lakes, rivers, coastline). Tables 3.2.3-1 and 3.2.3-2 contain emission information on commercial vessels falling into these three categories. Table 3.2.3-3 presents emission factors for diesel marine engines at various operating modes on the basis of horsepower. These data are applicable to any vessel having a similar size engine, not just to commercial vessels.

Unless a ship receives auxiliary steam from dockside facilities, goes immediately into drydock, or is out of operation after arrival in port, she continues her emissions at dockside. Power must be made available for the ship's lighting, heating, pumps, refrigeration, ventilation, etc. A few steam ships use auxiliary engines (diesel) to supply power, but they generally operate one or more main boilers under reduced draft and lowered fuel rates–a very inefficient process. Motorships (ships powered by internal combustion engines) normally use diesel-powered generators to furnish auxiliary power.[17] Emissions from these diesel-powered generators may also be a source of underway emissions if they are used away from port. Emissions from auxiliary power systems, in terms of the

Table 3.2.3-1. AVERAGE EMISSION FACTORS FOR COMMERCIAL MOTORSHIPS BY WATERWAY CLASSIFICATION
EMISSION FACTOR RATING: C

Emissions[a]	Class[c]		
	River	Great Lakes	Coastal
Sulfur oxides[b] (SO_x as SO_2)			
kg/10^3 liter	3.2	3.2	3.2
lb/10^3 gal	27	27	27
Carbon monoxide			
kg/10^3 liter	12	13	13
lb/10^3 gal	100	110	110
Hydrocarbons			
kg/10^3 liter	6.0	7.0	6.0
lb/10^3 gal	50	59	50
Nitrogen oxides (NO_x as NO_2)			
kg/10^3 liter	33	31	32
lb/10^3 gal	280	260	270

[a] Expressed as function of fuel consumed (based on emission data from Reference 2 and population/usage data from References 11 through 16.

[b] Calculated, not measured. Based on 0.20 percent sulfur content fuel and density of 0.854 kg/liter (7.12 lb/gal) from Reference 17.

[c] Very approximate particulate emission factors from Reference 2 are 470 g/hr (1.04 lb/hr). The reference does not contain sufficient information to calculate fuel-based factors.

quantity of fuel consumed, are presented in Table 3.2.3-4. In some instances, fuel quantities used may not be available, so calculation of emissions based on kilowatt hours (kWh) produced may be necessary. For operating loads in excess of zero percent, the mass emissions (e_1) in kilograms per hour (pounds per hour) are given by:

$$e_1 = kle_f \tag{1}$$

where: k = a constant that relates fuel consumption to kilowatt hours,[2]

that is, 3.63×10^{-4} 1000 liters fuel/kWh

or

9.59×10^{-5} 1000 gal fuel/kWh

l = the load, kW

e_f = the fuel-specific emission factor from Table 3.2.3-4, kg/10^3 liter (lb/10^3 gal)

Table 3.2.3-2. EMISSION FACTORS FOR COMMERCIAL STEAMSHIPS–ALL GEOGRAPHIC AREAS
EMISSION FACTOR RATING: D

	Fuel and operating mode[a]											
	Residual oil[b]						Distillate oil[b]					
	Hoteling		Cruise		Full		Hoteling		Cruise		Full	
Pollutant	kg/10^3 liter	lb/10^3 gal	kg/10^3 liter	lb/10^3 gal	kg/10^3 liter	lb/10^3 gal	kg/10^3 liter	lb/10^3 gal	kg/10^3 liter	lb/10^3 gal	kg/10^3 liter	lb/10^3 gal
Particulates[c]	1.20[d]	10.0[d]	2.40	20.0	6.78	56.5	1.8	15	1.78	15	1.78	15
Sulfur oxides (SO_x as SO_2)[e]	19.1S	159S	19.1S	159S	19.1S	159S	17.0S	142S	17.0S	142S	17.0S	142S
Carbon monoxide[c]	Neg[d]	Neg[d]	0.414	3.45	0.872	7.27	0.5	4	0.5	4	0.5	4
Hydrocarbons[c]	0.38[d]	3.2[d]	0.082	0.682	0.206	1.72	0.4	3	0.4	3	0.4	3
Nitrogen oxides (NO_x as NO_2)	4.37	36.4	6.70	55.8	7.63	63.6	2.66	22.2	2.83	23.6	5.34	44.5

[a] The operating modes are based on the percentage of maximum available power: "hoteling" is 10 to 11 percent of available power, "full" is 100 percent of available power, and "cruise" is an intermediate power (35 to 75 percent, depending on the test organization and vessel tested).

[b] Test organizations used "Navy Special" fuel oil, which is not a true residual oil. No vessel test data were available for residual oil combustion. "Residual" oil results are from References 2, 3, and 5. "Distillate" oil results are from References 3 and 5 only. Exceptions are noted. "Navy Distillate" was used as distillate test fuel.

[c] Particulate, carbon monoxide, and hydrocarbon emission factors for distillate oil combustion are based on stationary boilers (see Section 1.3 of this document).

[d] Reference 18 indicates that carbon monoxide emitted during hoteling is small enough to be considered negligible. This reference also places hydrocarbons at 0.38 kg/10^3 liter (3.2 lb/10^3 gal) and particulate at 1.20 kg/10^3 liter (10.0 lb/10^3 gal). These data are included for completeness only and are not necessarily comparable with other tabulated data.

[e] Emission factors listed are theoretical in that they are based on all the sulfur in the fuel converting to sulfur dioxide. Actual test data from References 3 and 5 confirm the validity of these theoretical factors. "S" is fuel sulfur content in percent.

Table 3.2.3-3. DIESEL VESSEL EMISSION FACTORS BY OPERATING MODE[a]
EMISSION FACTOR RATING: C

		Emissions[b]					
		Carbon monoxide		Hydrocarbons		Nitrogen oxides (NO_x as NO_2)	
Horsepower	Mode	lb/10^3 gal	kg/10^3 liter	lb/10^3 gal	kg/10^3 liter	lb/10^3 gal	kg/10^3 liter
200	Idle	210.3	25.2	391.2	46.9	6.4	0.8
	Slow	145.4	17.4	103.2	12.4	207.8	25.0
	Cruise	126.3	15.1	170.2	20.4	422.9	50.7
	Full	142.1	17.0	60.0	7.2	255.0	30.6
300	Slow	59.0	7.1	56.7	6.8	337.5	40.4
	Cruise	47.3	5.7	51.1	6.1	389.3	46.7
	Full	58.5	7.0	21.0	2.5	275.1	33.0
500	Idle	282.5	33.8	118.1	14.1	99.4	11.9
	Cruise	99.7	11.9	44.5	5.3	338.6	40.6
	Full	84.2	10.1	22.8	2.7	269.2	32.3
600	Idle	171.7	20.6	68.0	8.2	307.1	36.8
	Slow	50.8	6.1	16.6	2.0	251.5	30.1
	Cruise	77.6	9.3	24.1	2.9	349.2	41.8
700	Idle	293.2	35.1	95.8	11.5	246.0	29.5
	Cruise	36.0	4.3	8.8	1.1	452.8	54.2
900	Idle	223.7	26.8	249.1	29.8	107.5	12.9
	2/3	62.2	7.5	16.8	2.0	167.2	20.0
	Cruise	80.9	9.7	17.1	2.1	360.0	43.1
1550	Idle	12.2	1.5	–	–	39.9	4.8
	Cruise	3.3	0.4	0.64	0.1	36.2	4.3
	Full	7.0	0.8	1.64	0.2	37.4	4.5
1580	Slow	122.4	14.7	–	–	371.3	44.5
	Cruise	44.6	5.3	–	–	623.1	74.6
	Full	237.7	28.5	16.8	2.0	472.0	5.7
2500	Slow	59.8	7.2	22.6	2.7	419.6	50.3
	2/3	126.5	15.2	14.7	1.8	326.2	39.1
	Cruise	78.3	9.4	16.8	2.0	391.7	46.9
	Full	95.9	11.5	21.3	2.6	399.6	47.9
3600	Slow	148.5	17.8	60.0	7.2	367.0	44.0
	2/3	28.1	3.4	25.4	3.0	358.6	43.0
	Cruise	41.4	5.0	32.8	4.0	339.6	40.7
	Full	62.4	7.5	29.5	3.5	307.0	36.8

[a] Reference 2.

[b] Particulate and sulfur oxides data are not available.

Table 3.2.3-4. AVERAGE EMISSION FACTORS FOR DIESEL-POWERED ELECTRICAL GENERATORS IN VESSELS[a]
EMISSION FACTOR RATING: C

Rated output,[b] kW	Load,[c] % rated output	Emissions							
		Sulfur oxides (SO_x as SO_2)[d]		Carbon monoxide		Hydro-carbons		Nitrogen oxides (NO_x as NO_2)	
		$lb/10^3$ gal	$kg/10^3$ liter	$lb/10^3$ gal	$kg/10^3$ liter	$lb/10^3$ gal	$kg/10^3$ liter	$lb/10^3$ gal	$kg/10^3$ liter
20	0	27	3.2	150	18.0	263	31.5	434	52.0
	25	27	3.2	79.7	9.55	204	24.4	444	53.2
	50	27	3.2	53.4	6.40	144	17.3	477	57.2
	75	27	3.2	28.5	3.42	84.7	10.2	495	59.3
40	0	27	3.2	153	18.3	584	70.0	214	25.6
	25	27	3.2	89.0	10.7	370	44.3	219	26.2
	50	27	3.2	67.6	8.10	285	34.2	226	27.1
	75	27	3.2	64.1	7.68	231	27.7	233	27.9
200	0	27	3.2	134	16.1	135	16.2	142	17.0
	25	27	3.2	97.9	11.7	33.5	4.01	141	16.9
	50	27	3.2	62.3	7.47	17.8	2.13	140	16.8
	75	27	3.2	26.7	3.20	17.5	2.10	137	16.4
500	0	27	3.2	58.4	7.00	209	25.0	153	18.3
	25	27	3.2	53.4	6.40	109	13.0	222	26.6
	50	27	3.2	48.1	5.76	81.9	9.8	293	35.1
	75	27	3.2	43.7	5.24	59.1	7.08	364	43.6

[a] Reference 2.

[b] Maximum rated output of the diesel-powered generator.

[c] Generator electrical output (for example, a 20 kW generator at 50 percent load equals 10 kW output).

[d] Calculated, not measured, based on 0.20 percent fuel sulfur content and density of 0.854 kg/liter (7.12 lb/gal) from Reference 17.

At zero load conditions, mass emission rates (e_1) may be approximated in terms of kg/hr (lb/hr) using the following relationship:

$$e_1 = k l_{rated} e_f \qquad (2)$$

where: k = a constant that relates rated output and fuel consumption,

that is, 6.93×10^{-5} 1000 liters fuel/kW

or

1.83×10^{-5} 1000 gal fuel/kW

l_{rated} = the rated output, kW

e_f = the fuel-specific emission factor from Table 3.2.3-4, $kg/10^3$ liter ($lb/10^3$ gal)

Pleasure craft. Many of the engine designs used in inboard pleasure craft are also used either in military vessels (diesel) or in highway vehicles (gasoline). Out of a total of 700,000 inboard pleasure craft registered in the United States in 1972, nearly 300,000 were inboard/outdrive. According to sales data, 60 to 70 percent of these inboard/outdrive craft used gasoline-powered automotive engines rated at more than 130 horsepower.[6] The remaining 400,000 pleasure craft used conventional inboard drives that were powered by a variety of powerplants, both gasoline and diesel. Because emission data are not available for pleasure craft, Coast Guard and automotive data[2,19] are used to characterize emission factors for this class of vessels in Table 3.2.3-5.

Military vessels. Military vessels are powered by a wide variety of both diesel and steam power plants. Many of the emission data used in this section are the result of emission testing programs conducted by the U.S. Navy and the U.S. Coast Guard.[1-3,5] A separate table containing data on military vessels is not provided here, but the included tables should be sufficient to calculate approximate military vessel emissions.

TABLE 3.2.3.-5. AVERAGE EMISSION FACTORS FOR INBOARD PLEASURE CRAFT[a]

EMISSION FACTOR RATING: D

Pollutant	Based on fuel consumption				Based on operating time			
	Diesel engine[b]		Gasoline engine[c]					
	kg/10^3 liter	lb/10^3 gal	kg/10^3 liter	lb/10^3 gal	Diesel engine[b]		Gasoline engine[c]	
					kg/hr	lb/hr	kg/hr	lb/hr
Sulfur oxides[d] (SO_x as SO_2)	3.2	27	0.77	6.4	–	–	0.008	0.019
Carbon monoxide	17	140	149	1240	–	–	1.69	3.73
Hydrocarbons	22	180	10.3	86	–	–	0.117	0.258
Nitrogen oxides (NO_x as NO_2)	41	340	15.7	131	–	–	0.179	0.394

[a] Average emission factors are based on the duty cycle developed for large outboards (≥ 48 kilowatts or ≥ 65 horsepower) from Reference 7. The above factors take into account the impact of water scrubbing of underwater gasoline engine exhaust, also from Reference 7. All values given are for single engine craft and must be modified for multiple engine vessels.

[b] Based on tests of diesel engines in Coast Guard vessels, Reference 2.

[c] Based on tests of automotive engines, Reference 19. Fuel consumption of 11.4 liter/hr (3 gal/hr) assumed. The resulting factors are only *rough* estimates.

[d] Based on fuel sulfur content of 0.20 percent for diesel fuel and 0.043 percent for gasoline from References 7 and 17. Calculated using fuel density of 0.740 kg/liter (6.17 lb/gal) for gasoline and 0.854 kg/liter (7.12 lb/gal) for diesel fuel.

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2.4 Outboard-Powered Vessels

by David S. Kircher

3.2.4.1 General – Most of the approximately 7 million outboard motors in use in the United States are 2-stroke engines with an average available horsepower of about 25. Because of the predominately leisure-time use of outboard motors, emissions related to their operation occur primarily during nonworking hours, in rural areas, and during the three summer months. Nearly 40 percent of the outboards are operated in the states of New York, Texas, Florida, Michigan, California, and Minnesota. This distribution results in the concentration of a large portion of total nationwide outboard emissions in these states.[1]

3.2.4.2 Emissions – Because the vast majority of outboards have underwater exhaust, emission measurement is very difficult. The values presented in Table 3.2.4-1 are the approximate atmospheric emissions from outboards. These data are based on tests of four outboard motors ranging from 4 to 65 horsepower.[1] The emission results from these motors are a composite based on the nationwide breakdown of outboards by horsepower. Emission factors are presented two ways in this section: in terms of fuel use and in terms of work output (horsepower hour). The selection of the factor used depends on the source inventory data available. Work output factors are used when the number of outboards in use is available. Fuel-specific emission factors are used when fuel consumption data are obtainable.

Table 3.2.4-1. AVERAGE EMISSION FACTORS FOR OUTBOARD MOTORS[a]
EMISSION FACTOR RATING: B

	Based on fuel consumption		Based on work output[c]	
Pollutant[b]	lb/10^3 gal	kg/10^3 liter	g/hphr	g/metric hphr
Sulfur oxides[d] (SO_x as SO_2)	6.4	0.77	0.49	0.49
Carbon monoxide	3300	400	250	250
Hydrocarbons[e]	1100	130	85	85
Nitrogen oxides (NO_x as NO_2)	6.6	0.79	0.50	0.50

[a] Reference 1. Data in this table are emissions to the atmosphere. A portion of the exhaust remains behind in the water.

[b] Particulate emission factors are not available because of the problems involved with measurement from an underwater exhaust system but are considered negligible.

[c] Horsepower hours are calculated by multiplying the average power produced during the hours of usage by the population of outboards in a given area. In the absence of data specific to a given geographic area, the hphr value can be estimated using average nationwide values from Reference 1. Reference 1 reports the average power produced (not the available power) as 9.1 hp and the average annual usage per engine as 50 hours. Thus, hphr = (number of outboards) (9.1 hp) (50 hours/outboard-year). Metric hphr = 0.9863 hphr.

[d] Based on fuel sulfur content of 0.043 percent from Reference 2 and on a density of 6.17 lb/gal.

[e] Includes exhaust hydrocarbons only. No crankcase emissions occur because the majority of outboards are 2-stroke engines that use crankcase induction. Evaporative emissions are limited by the widespread use of unvented tanks.

References for sections 3.2.4

1. Hare, C.T. and K.J. Springer. Exhaust Emissions from Uncontrolled Vehicles and Related Equipment Using Internal Combustion Engines. Part II, Outboard Motors. Final Report. Southwest Research Institute. San Antonio, Texas. Prepared for the Environmental Protection Agency, Research Triangle Park, N.C., under Contract Number EHS 70-108. January 1973.

2. Hare, C.T. and K.J. Springer. Study of Exhaust Emissions from Uncontrolled Vehicles and Related Equipment Using Internal Combustion Engines. Emission Factors and Impact Estimates for Light-Duty Air-Cooled Utility Engines and Motorcycles. Southwest Research Institute. San Antonio, Texas. Prepared for the Environmental Protection Agency, Research Triangle Park, N.C., under Contract Number EHS 70-108. January 1972.

3.2.5 Small, General Utility Engines

Revised by Charles C. Masser

3.2.5.1 General–This category of engines comprises small 2-stroke and 4-stroke, air-cooled, gasoline-powered motors. Examples of the uses of these engines are: lawnmowers, small electric generators, compressors, pumps, minibikes, snowthrowers, and garden tractors. This category does *not* include motorcycles, outboard motors, chain saws, and snowmobiles, which are either included in other parts of this chapter or are not included because of the lack of emission data.

Approximately 89 percent of the more than 44 million engines of this category in service in the United States are used in lawn and garden applications.[1]

3.2.5.2 Emissions–Emissions from these engines are reported in Table 3.2.5-1. For the purpose of emission estimation, engines in this category have been divided into lawn and garden (2-stroke), lawn and garden (4-stroke), and miscellaneous (4-stroke). Emission factors are presented in terms of horsepower hours, annual usage, and fuel consumption.

References for Section 3.2.5

1. Donohue, J. A., G. C. Hardwick, H. K. Newhall, K. S. Sanvordenker, and N. C. Woelffer. Small Engine Exhaust Emissions and Air Quality in the United States. (Presented at the Automotive Engineering Congress, Society of Automotive Engineers, Detroit. January 1972.)

2. Hare, C. T. and K. J. Springer. Study of Exhaust Emissions from Uncontrolled Vehicles and Related Equipment Using Internal Combustion Engines. Part IV. Small Air-Cooled Spark Ignition Utility Engines. Final Report. Southwest Research Institute. San Antonio, Tex. Prepared for the Environmental Protection Agency, Research Triangle Park, N.C., under Contract No. EHS 70-108. May 1973.

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Table 3.2.5-1. EMISSION FACTORS FOR SMALL, GENERAL UTILITY ENGINES[a,b]
EMISSION FACTOR RATING: B

Engine	Sulfur oxides[c] (SO_x as SO_2)	Particulate	Carbon monoxide	Hydrocarbons		Nitrogen oxides (NO_x as NO_2)	Aldehydes (HCHO)
				Exhaust	Evaporative[d]		
2-Stroke, lawn and garden							
g/hphr	0.54	7.1	486	214	–	1.58	2.04
g/metric hphr	0.54	7.1	486	214	–	1.58	2.04
g/gal of fuel	1.80	23.6	1,618	713	–	5.26	6.79
g/unit-year	38	470	33,400	14,700	113	108	140
4-Stroke, lawn and garden							
g/hphr	0.37	0.44	279	23.2	–	3.17	0.49
g/metric hphr	0.37	0.44	279	23.2	–	3.17	0.49
g/gal of fuel	2.37	2.82	1,790	149	–	20.3	3.14
g/unit-year	26	31	19,100	1,590	113	217	34
4-Stroke miscellaneous							
g/hphr	0.39	0.44	250	15.2	–	4.97	0.47
g/metric hphr	0.39	0.44	250	15.2	–	4.97	0.47
g/gal of fuel	2.45	2.77	1,571	95.5	–	31.2	2.95
g/unit-year	30	34	19,300	1,170	290	384	36

[a] Reference 2.

[b] Values for g/unit-year were calculated assuming an annual usage of 50 hours and a 40 percent load factor. Factors for g/hphr can be used in instances where annual usages, load factors, and rated horsepower are known. Horsepower hours are the product of the usage in hours, the load factor, and the rated horsepower.

[c] Values calculated, not measured, based on the use of 0.043 percent sulfur content fuel.

[d] Values calculated from annual fuel consumption. Evaporative losses from storage and filling operations are not included (see Chapter 4).

3.2.6 Agricultural Equipment

by David S. Kircher

3.2.6.1 General – Farm equipment can be separated into two major categories: wheeled tractors and other farm machinery. In 1972, the wheeled tractor population on farms consisted of 4.5 million units with an average power of approximately 34 kilowatts (45 horsepower). Approximately 30 percent of the total population of these tractors is powered by diesel engines. The average diesel tractor is more powerful than the average gasoline tractor, that is, 52 kW (70 hp) versus 27 kW (36 hp).[1] A considerable amount of population and usage data is available for farm tractors. For example, the Census of Agriculture reports the number of tractors in use for each county in the U.S.[2] Few data are available on the usage and numbers of non-tractor farm equipment, however. Self-propelled combines, forage harvesters, irrigation pumps, and auxiliary engines on pull-type combines and balers are examples of non-tractor agricultural uses of internal combustion engines. Table 3.2.6-1 presents data on this equipment for the U.S.

3.2.6.2 Emissions – Emission factors for wheeled tractors and other farm machinery are presented in Table 3.2.6-2. Estimating emissions from the time-based emission factors–grams per hour (g/hr) and pounds per hour (lb/hr)–requires an average usage value in hours. An approximate figure of 550 hours per year may be used or, on the basis of power, the relationship, usage in hours = 450 + 5.24 (kW - 37.2) or usage in hours = 450 + 3.89 (hp - 50) may be employed.[1]

The best emissions estimates result from the use of "brake specific" emission factors (g/kWh or g/hphr). Emissions are the product of the brake specific emission factor, the usage in hours, the power available, and the load factor (power used divided by power available). Emissions are also reported in terms of fuel consumed.

Table 3.2.6-1. SERVICE CHARACTERISTICS OF FARM EQUIPMENT (OTHER THAN TRACTORS)[a]

Machine	Units in service, x10^3	Typical size	Typical power		Percent gasoline	Percent diesel
			kW	hp		
Combine, self-propelled	434	4.3 m (14 ft)	82	110	50	50
Combine, pull type	289	2.4 m (8 ft)	19	25	100	0
Corn pickers and picker-shellers	687	2-row	–[b]	–	–	–
Pick-up balers	655	5400 kg/hr (6 ton/hr)	30	40	100	0
Forage harvesters	295	3.7 m (12 ft) or 3-row	104	140	0	100
Miscellaneous	1205	–	22	30	50	50

[a] Reference 1.

[b] Unpowered.

Table 3.2.6-2. EMISSION FACTORS FOR WHEELED FARM TRACTORS AND NON-TRACTOR AGRICULTURAL EQUIPMENT[a]

EMISSION FACTOR RATING: C

Pollutant	Diesel farm tractor	Gasoline farm tractor	Diesel farm equipment (non-tractor)	Gasoline farm equipment (non-tractor)
Carbon monoxide				
g/hr	161	3,380	95.2	4,360
lb/hr	0.355	7.46	0.210	9.62
g/kWh	4.48	192	5.47	292
g/hphr	3.34	143	4.08	218
$kg/10^3$ liter	14.3	391	16.7	492
$lb/10^3$ gal	119	3,260	139	4,100
Exhaust hydrocarbons				
g/hr	77.8	128	38.6	143
lb/hr	0.172	0.282	0.085	0.315
g/kWh	2.28	7.36	2.25	9.63
g/hphr	1.70	5.49	1.68	7.18
$kg/10^3$ liter	7.28	15.0	6.85	16.2
$lb/10^3$ gal	60.7	125	57.1	135
Crankcase hydrocarbons[b]				
g/hr	–	26.0	–	28.6
lb/hr	–	0.057	–	0.063
g/kWh	–	1.47	–	1.93
g/hphr	–	1.10	–	1.44
$kg/10^3$ liter	–	3.01	–	3.25
$lb/10^3$ gal	–	25.1	–	27.1
Evaporative hydrocarbons[b]				
g/unit-year	–	15,600	–	1,600
lb/unit-year	–	34.4	–	3.53
Nitrogen oxides (NO_x as NO_2)				
g/hr	452	157	210	105
lb/hr	0.996	0.346	0.463	0.231
g/kWh	12.6	8.88	12.11	7.03
g/hphr	9.39	6.62	9.03	5.24
$kg/10^3$ liter	40.2	18.1	36.8	11.8
$lb/10^3$ gal	335	151	307	98.5
Aldehydes (RCHO as HCHO)				
g/hr	16.3	7.07	7.23	4.76
lb/hr	0.036	0.016	0.016	0.010
g/kWh	0.456	0.402	0.402	0.295
g/hphr	0.340	0.300	0.30	0.220
$kg/10^3$ liter	1.45	0.821	1.22	0.497
$lb/10^3$ gal	12.1	6.84	10.2	4.14
Sulfur oxides[c] (SO_x as SO_2)				
g/hr	42.2	5.56	21.7	6.34
lb/hr	0.093	0.012	0.048	0.014

Table 3.2.6-2. (continued). EMISSION FACTORS FOR WHEELED FARM TRACTORS AND NON-TRACTOR AGRICULTURAL EQUIPMENT[a]

EMISSION FACTOR RATING: C

Pollutant	Diesel farm tractor	Gasoline farm tractor	Diesel farm equipment (non-tractor)	Gasoline farm equipment (non-tractor)
g/kWh	1.17	0.312	1.23	0.377
g/hphr	0.874	0.233	0.916	0.281
$kg/10^3$ liter	3.74	0.637	3.73	0.634
$lb/10^3$ gal	31.2	5.31	31.1	5.28
Particulate				
g/hr	61.8	8.33	34.9	7.94
lb/hr	0.136	0.018	0.077	0.017
g/kWh	1.72	0.471	2.02	0.489
g/hphr	1.28	0.361	1.51	0.365
$kg/10^3$ liter	5.48	0.960	6.16	0.823
$lb/10^3$ gal	45.7	8.00	51.3	6.86

[a] Reference 1.

[b] Crankcase and evaporative emissions from diesel engines are considered negligible.

[c] Not measured. Calculated from fuel sulfur content of 0.043 percent and 0.22 percent for gasoline-powered and diesel-powered equipment, respectively.

References for Section 3.2.6

1. Hare, C. T. and K. J. Springer. Exhaust Emissions from Uncontrolled Vehicles and Related Equipment Using Internal Combustion Engines. Final Report. Part 5: Heavy-Duty Farm, Construction and Industrial Engines. Southwest Research Institute, San Antonio, Tex. Prepared for Environmental Protection Agency, Research Triangle Park, N.C., under Contract No. EHS 70-108. August 1973. 97 p.

2. County Farm Reports. U.S. Census of Agriculture. U.S. Department of Agriculture. Washington, D.C.

3.2.7 Heavy-Duty Construction Equipment

by David S. Kircher

3.2.7.1 General – Because few sales, population, or usage data are available for construction equipment, a number of assumptions were necessary in formulating the emission factors presented in this section.[1] The useful life of construction equipment is fairly short because of the frequent and severe usage it must endure. The annual usage of the various categories of equipment considered here ranges from 740 hours (wheeled tractors and rollers) to 2000 hours (scrapers and off-highway trucks). This high level of use results in average vehicle lifetimes of only 6 to 16 years. The equipment categories in this section include: tracklaying tractors, tracklaying shovel loaders, motor graders, scrapers, off-highway trucks, wheeled loaders, wheeled tractors, rollers, wheeled dozers, and miscellaneous machines. The latter category contains a vast array of less numerous mobile and semi-mobile machines used in construction, such as, belt loaders, cranes, pumps, mixers, and generators. With the exception of rollers, the majority of the equipment within each category is diesel-powered.

3.2.7.2 Emissions -- Emission factors for heavy-duty construction equipment are reported in Table 3.2.7-1 for diesel engines and in Table 3.2.7-2 for gasoline engines. The factors are reported in three different forms–on the basis of running time, fuel consumed, and power consumed. In order to estimate emissions from time-based emission factors, annual equipment usage in hours must be estimated. The following estimates of use for the equipment listed in the tables should permit reasonable emission calculations.

Category	Annual operation, hours/year
Tracklaying tractors	1050
Tracklaying shovel loaders	1100
Motor graders	830
Scrapers	2000
Off-highway trucks	2000
Wheeled loaders	1140
Wheeled tractors	740
Rollers	740
Wheeled dozers	2000
Miscellaneous	1000

The best method for calculating emissions, however, is on the basis of "brake specific" emission factors (g/kWh or g/hphr). Emissions are calculated by taking the product of the brake specific emission factor, the usage in hours, the power available (that is, rated power), and the load factor (the power actually used divided by the power available).

References for Section 3.2.7

1. Hare, C. T. and K. J. Springer. Exhaust Emissions from Uncontrolled Vehicles and Related Equipment Using Internal Combustion Engines – Final Report. Part 5: Heavy-Duty Farm, Construction, and Industrial Engines. Southwest Research Institute, San Antonio, Tex. Prepared for Environmental Protection Agency, Research Triangle Park, N.C., under Contract No. EHS 70-108. October 1973. 105 p.

2. Hare, C. T. Letter to C. C. Masser of Environmental Protection Agency, Research Triangle Park, N.C., concerning fuel-based emission rates for farm, construction, and industrial engines. San Antonio, Tex. January 14, 1974. 4 p.

Table 3.2.7-1. EMISSION FACTORS FOR HEAVY-DUTY, DIESEL-POWERED CONSTRUCTION EQUIPMENT[a]

EMISSION FACTOR RATING: C

Pollutant	Tracklaying tractor	Wheeled tractor	Wheeled dozer	Scraper	Motor grader
Carbon monoxide					
g/hr	175.	973.	335.	660.	97.7
lb/hr	0.386	2.15	0.739	1.46	0.215
g/kWh	3.21	5.90	2.45	3.81	2.94
g/hphr	2.39	4.40	1.83	2.84	2.19
kg/10^3 liter	10.5	19.3	7.90	11.8	9.35
lb/10^3 gal	87.5	161.	65.9	98.3	78.0
Exhaust hydrocarbons					
g/hr	50.1	67.2	106.	284.	24.7
lb/hr	0.110	0.148	0.234	0.626	0.054
g/kWh	0.919	1.86	0.772	1.64	0.656
g/hphr	0.685	1.39	0.576	1.22	0.489
kg/10^3 liter	3.01	6.10	2.48	5.06	2.09
lb/10^3 gal	25.1	50.9	20.7	42.2	17.4
Nitrogen oxides (NO_x as NO_2)					
g/hr	665.	451.	2290.	2820.	478.
lb/hr	1.47	0.994	5.05	6.22	1.05
g/kWh	12.2	12.5	16.8	16.2	14.1
g/hphr	9.08	9.35	12.5	12.1	10.5
kg/10^3 liter	39.8	41.0	53.9	50.2	44.8
lb/10^3 gal	332.	342.	450.	419.	374.
Aldehydes (RCHO as HCHO)					
g/hr	12.4	13.5	29.5	65.	5.54
lb/hr	0.027	0.030	0.065	0.143	0.012
g/kWh	0.228	0.378	0.215	0.375	0.162
g/hphr	0.170	0.282	0.160	0.280	0.121
kg/10^3 liter	0.745	1.23	0.690	1.16	0.517
lb/10^3 gal	6.22	10.3	5.76	9.69	4.31
Sulfur oxides (SO_x as SO_2)					
g/hr	62.3	40.9	158.	210.	39.0
lb/hr	0.137	0.090	0.348	0.463	0.086
g/kWh	1.14	1.14	1.16	1.21	1.17
g/hphr	0.851	0.851	0.867	0.901	0.874
kg/10^3 liter	3.73	3.73	3.74	3.74	3.73
lb/10^3 gal	31.1	31.1	31.2	31.2	31.1
Particulate					
g/hr	50.7	61.5	75.	184.	27.7
lb/hr	0.112	0.136	0.165	0.406	0.061
g/kWh	0.928	1.70	0.551	1.06	0.838
g/hphr	0.692	1.27	0.411	0.789	0.625
kg/10^3 liter	3.03	5.57	1.77	3.27	2.66
lb/10^3 gal	25.3	46.5	14.8	27.3	22.2

[a] References 1 and 2.

Table 3.2.7-1 (continued). EMISSION FACTORS FOR HEAVY-DUTY, DIESEL-POWERED CONSTRUCTION EQUIPMENT[a]

EMISSION FACTOR RATING: C

Pollutant	Wheeled loader	Tracklaying loader	Off-Highway truck	Roller	Miscellaneous
Carbon monoxide					
g/hr	251.	72.5	610.	83.5	188.
lb/hr	0.553	0.160	1.34	0.184	0.414
g/kWh	3.51	2.41	3.51	4.89	3.78
g/hphr	2.62	1.80	2.62	3.65	2.82
kg/10^3 liter	11.4	7.90	11.0	13.7	11.3
lb/10^3 gal	95.4	65.9	92.2	114.	94.2
Exhaust hydrocarbons					
g/hr	84.7	14.5	198.	24.7	71.4
lb/hr	0.187	0.032	0.437	0.054	0.157
g/kWh	1.19	0.485	1.14	1.05	1.39
g/hphr	0.888	0.362	0.853	0.781	1.04
kg/10^3 liter	3.87	1.58	3.60	2.91	4.16
lb/10^3 gal	32.3	13.2	30.0	24.3	34.7
Nitrogen oxides (NO_x as NO_2)					
g/hr	1090.	265.	3460.	474.	1030.
lb/hr	2.40	0.584	7.63	1.04	2.27
g/kWh	15.0	8.80	20.0	21.1	19.8
g/hphr	11.2	6.56	14.9	15.7	14.8
kg/10^3 liter	48.9	28.8	62.8	58.5	59.2
lb/10^3 gal	408.	240.	524.	488.	494.
Aldehydes (RCHO as HCHO)					
g/hr	18.8	4.00	51.0	7.43	13.9
lb/hr	0.041	0.009	0.112	0.016	0.031
g/kWh	0.264	0.134	0.295	0.263	0.272
g/hphr	0.197	0.100	0.220	0.196	0.203
kg/10^3 liter	0.859	0.439	0.928	0.731	0.813
lb/10^3 gal	7.17	3.66	7.74	6.10	6.78
Sulfur oxides (SO_x as SO_2)					
g/hr	82.5	34.4	206.	30.5	64.7
lb/hr	0.182	0.076	0.454	0.067	0.143
g/kWh	1.15	1.14	1.19	1.34	1.25
g/hphr	0.857	0.853	0.887	1.00	0.932
kg/10^3 liter	3.74	3.74	3.74	3.73	3.73
lb/10^3 gal	31.2	31.2	31.2	31.1	31.1
Particulate					
g/hr	77.9	26.4	116.	22.7	63.2
lb/hr	0.172	0.058	0.256	0.050	0.139
g/kWh	1.08	0.878	0.673	1.04	1.21
g/hphr	0.805	0.655	0.502	0.778	0.902
kg/10^3 liter	3.51	2.88	2.12	2.90	3.61
lb/10^3 gal	29.3	24.0	17.7	24.2	30.1

[a] References 1 and 2.

Table 3.2.7-2. EMISSION FACTORS FOR HEAVY-DUTY GASOLINE-POWERED CONSTRUCTION EQUIPMENT[a]
EMISSION FACTOR RATING: C

Pollutant	Wheeled tractor	Motor grader	Wheeled loader	Roller	Miscel- laneous
Carbon monoxide					
g/hr	4320.	5490.	7060.	6080.	7720.
lb/hr	9.52	12.1	15.6	13.4	17.0
g/kWh	190.	251.	219.	271.	266.
g/hphr	142.	187.	163.	202.	198.
kg/10^3 liter	389.	469.	435.	460.	475.
lb/10^3 gal	3250.	3910.	3630.	3840.	3960.
Exhaust hydrocarbons					
g/hr	164.	186.	241.	277.	254.
lb/hr	0.362	0.410	0.531	0.611	0.560
g/kWh	7.16	8.48	7.46	12.40	8.70
g/hphr	5.34	6.32	5.56	9.25	6.49
kg/10^3 liter	14.6	15.8	14.9	21.1	15.6
lb/10^3 gal	122.	132.	124.	176.	130.
Evaporative hydrocarbons[b]					
g/hr	30.9	30.0	29.7	28.2	25.4
lb/hr	0.0681	0.0661	0.0655	0.0622	0.0560
Crankcase hydrocarbons[b]					
g/hr	32.6	37.1	48.2	55.5	50.7
lb/hr	0.0719	0.0818	0.106	0.122	0.112
Nitrogen oxides (NO_x as NO_2)					
g/hr	195.	145.	235.	164.	187.
lb/hr	0.430	0.320	0.518	0.362	0.412
g/kWh	8.54	6.57	7.27	7.08	6.42
g/hphr	6.37	4.90	5.42	5.28	4.79
kg/10^3 liter	17.5	12.2	14.5	12.0	11.5
lb/10^3 gal	146.	102.	121.	100.	95.8
Aldehydes (RCHO as HCHO)					
g/hr	7.97	8.80	9.65	7.57	9.00
lb/hr	0.0176	0.0194	0.0213	0.0167	0.0198
g/kWh	0.341	0.386	0.298	0.343	0.298
g/hphr	0.254	0.288	0.222	0.256	0.222
kg/10^3 liter	0.697	0.721	0.593	0.582	0.532
lb/10^3 gal	5.82	6.02	4.95	4.86	4.44
Sulfur oxides (SO_x as SO_2)					
g/hr	7.03	7.59	10.6	8.38	10.6
lb/hr	0.0155	0.0167	0.0234	0.0185	0.0234
g/kWh	0.304	0.341	0.319	0.373	0.354
g/hphr	0.227	0.254	0.238	0.278	0.264
kg/10^3 liter	0.623	0.636	0.636	0.633	0.633
lb/10^3 gal	5.20	5.31	5.31	5.28	5.28

Table 3.2.7-2. (continued). EMISSION FACTORS FOR HEAVY-DUTY GASOLINE-POWERED CONSTRUCTION EQUIPMENT[a]

EMISSION FACTOR RATING: C

Pollutant	Wheeled tractor	Motor grader	Wheeled loader	Roller	Miscel-laneous
Particulate					
g/hr	10.9	9.40	13.5	11.8	11.7
lb/hr	0.0240	0.0207	0.0298	0.0260	0.0258
g/kWh	0.484	0.440	0.421	0.527	0.406
g/hphr	0.361	0.328	0.314	0.393	0.303
kg/10^3 liter	0.991	0.822	0.839	0.895	0.726
lb/10^3 gal	8.27	6.86	7.00	7.47	6.06

[a] References 1 and 2.

[b] Evaporative and crankcase hydrocarbons based on operating time only (Reference 1).

3.2.8 Snowmobiles

by Charles C. Masser

3.2.8.1 General – In order to develop emission factors for snowmobiles, mass emission rates must be known, and operating cycles representative of usage in the field must be either known or assumed. Extending the applicability of data from tests of a few vehicles to the total snowmobile population requires additional information on the composition of the vehicle population by engine size and type. In addition, data on annual usage and total machine population are necessary when the effect of this source on national emission levels is estimated.

An accurate determination of the number of snowmobiles in use is quite easily obtained because most states require registration of the vehicles. The most notable features of these registration data are that almost 1.5 million sleds are operated in the United States, that more than 70 percent of the snowmobiles are registered in just four states (Michigan, Minnesota, Wisconsin, and New York), and that only about 12 percent of all snowmobiles are found in areas outside the northeast and northern midwest.

3.2.8.2 Emissions – Operating data on snowmobiles are somewhat limited, but enough are available so that an attempt can be made to construct a representative operating cycle. The required end products of this effort are time-based weighting factors for the speed/load conditions at which the test engines were operated; use of these factors will permit computation of "cycle composite" mass emissions, power consumption, fuel consumption, and specific pollutant emissions.

Emission factors for snowmobiles were obtained through an EPA-contracted study[1] in which a variety of snowmobile engines were tested to obtain exhaust emissions data. These emissions data along with annual usage data were used by the contractor to estimate emission factors and the nationwide emission impact of this pollutant source.

To arrive at average emission factors for snowmobiles, a reasonable estimate of average engine size was necessary. Weighting the size of the engine to the degree to which each engine is assumed to be representative of the total population of engines in service resulted in an estimated average displacement of 362 cubic centimeters (cm^3).

The speed/load conditions at which the test engines were operated represented, as closely as possible, the normal operation of snowmobiles in the field. Calculations using the fuel consumption data obtained during the tests and the previously approximated average displacement of 362 cm^3 resulted in an estimated average fuel consumption of 0.94 gal/hr.

To compute snowmobile emission factors on a gram per unit year basis, it is necessary to know not only the emission factors but also the annual operating time. Estimates of this usage are discussed in Reference 1. On a national basis, however, average snowmobile usage can be assumed to be 60 hours per year. Emission factors for snowmobiles are presented in Table 3.2.8-1.

References for Section 3.2.8

1. Hare, C. T. and K. J. Springer. Study of Exhaust Emissions from Uncontrolled Vehicles and Related Equipment Using Internal Combustion Engines. Final Report. Part 7: Snowmobiles. Southwest Research Institute, San Antonio, Tex. Prepared for Environmental Protection Agency, Research Triangle Park, N.C., under Contract No. EHS 70-108. April 1974.

Table 3.2.8-1. EMISSION FACTORS FOR SNOWMOBILES
EMISSION FACTOR RATING: B

Pollutant	Emissions			
	g/unit-year[a]	g/gal[b]	g/liter[b]	g/hr[b]
Carbon monoxide	58,700	1,040.	275.	978.
Hydrocarbons	37,800	670.	177.	630.
Nitrogen oxides	600	10.6	2.8	10.0
Sulfur oxides[c]	51	0.90	0.24	0.85
Solid particulate	1,670	29.7	7.85	27.9
Aldehydes (RCHO)	552	9.8	2.6	9.2

[a] Based on 60 hours of operation per year and 362 cm^3 displacement.

[b] Based on 362 cm^3 displacement and average fuel consumption of 0.94 gal/hr.

[c] Based on sulfur content of 0.043 percent by weight.

3.3 OFF-HIGHWAY, STATIONARY SOURCES

by David S. Kircher and
Charles C. Masser

In general, engines included in this category are internal combustion engines used in applications similar to those associated with external combustion sources (see Chapter 1). The major engines within this category are gas turbines and large, heavy-duty, general utility reciprocating engines. Emission data currently available for these engines are limited to gas turbines and natural-gas-fired, heavy-duty, general utility engines. Most stationary internal combustion engines are used to generate electric power, to pump gas or other fluids, or to compress air for pneumatic machinery.

3.3.1 Stationary Gas Turbines for Electric Utility Power Plants

3.3.1.1 General – Stationary gas turbines find application in electric power generators, in gas pipeline pump and compressor drives, and in various process industries. The majority of these engines are used in electrical generation for continuous, peaking, or standby power.[1] The primary fuels used are natural gas and No. 2 (distillate) fuel oil, although residual oil is used in a few applications.

3.3.1.2 Emissions – Data on gas turbines were gathered and summarized under an EPA contract.[2] The contractor found that several investigators had reported data on emissions from gas turbines used in electrical generation but that little agreement existed among the investigators regarding the terms in which the emissions were expressed. The efforts represented by this section include acquisition of the data and their conversion to uniform terms. Because many sets of measurements reported by the contractor were not complete, this conversion often involved assumptions on engine air flow or fuel flow rates (based on manufacturers' data). Another shortcoming of the available information was that relatively few data were obtained at loads below maximum rated (or base) load.

Available data on the population and usage of gas turbines in electric utility power plants are fairly extensive, and information from the various sources appears to be in substantial agreement. The source providing the most complete information is the Federal Power Commission, which requires major utilities (electric revenues of $1 million or more) to submit operating and financial data on an annual basis. Sawyer and Farmer[3] employed these data to develop statistics on the use of gas turbines for electric generation in 1971. Although their report involved only the major, publicly owned utilities (not the private or investor-owned companies), the statistics do appear to include about 87 percent of the gas turbine power used for electric generation in 1971.

Of the 253 generating stations listed by Sawyer and Farmer, 137 have more than one turbine-generator unit. From the available data, it is not possible to know how many hours *each* turbine was operated during 1971 for these multiple-turbine plants. The remaining 116 (single-turbine) units, however, were operated an average of 1196 hours during 1971 (or 13.7 percent of the time), and their average load factor (percent of rated load) during operation was 86.8 percent. This information alone is not adequate for determining a representative operating pattern for electric utility turbines, but it should help prevent serious errors.

Using 1196 hours of operation per year and 250 starts per year as normal, the resulting average operating day is about 4.8 hours long. One hour of no-load time per day would represent about 21 percent of operating time, which is considered somewhat excessive. For economy considerations, turbines are not run at off-design conditions any longer than necessary, so time spent at intermediate power points is probably minimal. The bulk of turbine operation must be at base or peak load to achieve the high load factor already mentioned.

If it is assumed that time spent at off-design conditions includes 15 percent at zero load and 2 percent each at 25 percent, 50 percent, and 75 percent load, then the percentages of operating time at rated load (100 percent) and peak load (assumed to be 125 percent of rated) can be calculated to produce an 86.8 percent load factor. These percentages turn out to be 19 percent at peak load and 60 percent at rated load; the postulated cycle based on this line of reasoning is summarized in Table 3.3.1-1.

Table 3.3.1-1. TYPICAL OPERATING CYCLE FOR ELECTRIC UTILITY TURBINES

Condition, % of rated power	Percent operating time spent at condition	Time at condition based on 4.8-hr day		Contribution to load factor at condition
		hours	minutes	
0	15	0.72	43	0.00 x 0.15 = 0.0
25	2	0.10	6	0.25 x 0.02 = 0.005
50	2	0.10	6	0.50 x 0.02 = 0.010
75	2	0.10	6	0.75 x 0.02 = 0.015
100 (base)	60	2.88	173	1.0 x 0.60 = 0.60
125 (peak)	19	0.91	55	1.25 x 0.19 = 0.238
		4.81	289	Load factor = 0.868

The operating cycle in Table 3.3.1-1 is used to compute emission factors, although it is only an estimate of actual operating patterns.

Table 3.3.1-2. COMPOSITE EMISSION FACTORS FOR 1971 POPULATION OF ELECTRIC UTILITY TURBINES EMISSION FACTOR RATING: B

Time basis	Nitrogen oxides	Hydro-carbons	Carbon Monoxide	Partic-ulate	Sulfur oxides
Entire population					
lb/hr rated load[a]	8.84	0.79	2.18	0.52	0.33
kg/hr rated load	4.01	0.36	0.99	0.24	0.15
Gas-fired only					
lb/hr rated load	7.81	0.79	2.18	0.27	0.098
kg/hr rated load	3.54	0.36	0.99	0.12	0.044
Oil-fired only					
lb/hr rated load	9.60	0.79	2.18	0.71	0.50
kg/hr rated load	4.35	0.36	0.99	0.32	0.23
Fuel basis					
Gas-fired only					
lb/10^6 ft^3 gas	413.	42.	115.	14.	940S[b]
kg/10^6 m^3 gas	6615.	673.	1842.	224.	15,000S
Oil-fired only					
lb/10^3 gal oil	67.8	5.57	15.4	5.0	140S
kg/10^3 liter oil	8.13	0.668	1.85	0.60	16.8S

[a] Rated load expressed in megawatts.

[b] S is the percentage sulfur. Example: If the factor is 940 and the sulfur content is 0.01 percent, the sulfur oxides emitted would be 940 times 0.01, or 9.4 lb/10^6 ft^3 gas.

Table 3.3.1-2 is the resultant composite emission factors based on the operating cycle of Table 3.3.1-1 and the 1971 population of electric utility turbines.

Different values for time at base and peak loads are obtained by changing the total time at lower loads (0 through 75 percent) or by changing the distribution of time spent at lower loads. The cycle given in Table 3.3.1-1 seems reasonable, however, considering the fixed load factor and the economies of turbine operation. Note that the cycle determines *only* the importance of each load condition in computing composite emission factors for each type of turbine, *not* overall operating hours.

The top portion of Table 3.3.1-2 gives separate factors for gas-fired and oil-fired units, and the bottom portion gives fuel-based factors that can be used to estimate emission rates when overall fuel consumption data are available. Fuel-based emission factors on a mode basis would also be useful but present fuel consumption data are not adequate for this purpose.

References for Section 3.3.1

1. O'Keefe, W. and R. G. Schwieger. Prime Movers. Power. *115*(11): 522-531. November 1971.

2. Hare, C. T. and K. J. Springer. Exhaust Emissions from Uncontrolled Vehicles and Related Equipment Using Internal Combustion Engines. Final Report. Part 6: Gas Turbine Electric Utility Power Plants. Southwest Research Institute, San Antonio, Tex. Prepared for Environmental Protection Agency, Research Triangle Park, N.C., under Contract No. EHS 70-108, February 1974.

3. Sawyer, V. W. and R. C. Farmer. Gas Turbines in U.S. Electric Utilities. Gas Turbine International. January – April 1973.

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3.3.2 Heavy-Duty, Natural-Gas-Fired Pipeline Compressor Engines

by Susan Sercer
Alan Burgess
Tom Lahre

3.3.2.1 General[1] – Engines in the natural gas industry are used primarily to power compressors used for pipeline transportation, field gathering (collecting gas from wells), underground storage, and gas processing plant applications. Pipeline engines are concentrated in the major gas producing states (such as those along the Gulf Coast) and along the major gas pipelines. Both reciprocating engines and gas turbines are utilized, but the trend has been toward use of large gas turbines. Gas turbines emit considerably fewer pollutants than do reciprocating engines; however, reciprocating engines are generally more efficient in their use of fuel.

3.3.2.2 Emissions and Controls[1,2] – The primary pollutant of concern is NO_x, which readily forms in the high temperature, pressure, and excess air environment found in natural-gas-fired compressor engines. Lesser amounts of carbon monoxide and hydrocarbons are emitted, although for each unit of natural gas burned, compressor engines (particularly reciprocating engines) emit significantly more of these pollutants than do external combustion boilers. Sulfur oxides emissions are proportional to the sulfur content of the fuel and will usually be quite low because of the negligible sulfur content of most pipeline gas.

The major variables affecting NO_x emissions from compressor engines include the air fuel ratio, engine load (defined as the ratio of the operating horsepower divided by the rated horsepower), intake (manifold) air temperature, and absolute humidity. In general, NO_x emissions increase with increasing load and intake air temperature and decrease with increasing absolute humidity and air fuel ratio. (The latter already being, in most compressor engines, on the "lean" side of that air fuel ratio at which maximum NO_x formation occurs.) Quantitative estimates of the effects of these variables are presented in Reference 2.

Because NO_x is the primary pollutant of significance emitted from pipeline compressor engines, control measures to date have been directed mainly at limiting NO_x emissions. For gas turbines, the most effective method of controlling NO_x emissions is the injection of water into the combustion chamber. Nitrogen oxides reductions as high as 80 percent can be achieved by this method. Moreover, water injection results in only nominal reductions in overall turbine efficiency. Steam injection can also be employed, but the resulting NO_x reductions may not be as great as with water injection, and it has the added disadvantage that a supply of steam must be readily available. Exhaust gas recirculation, wherein a portion of the exhaust gases is recirculated back into the intake manifold, may result in NO_x reductions of up to 50 percent. This technique, however, may not be practical in many cases because the recirculated gases must be cooled to prevent engine malfunction. Other combustion modifications, designed to reduce the temperature and/or residence time of the combustion gases, can also be effective in reducing NO_x emissions by 10 to 40 percent in specific gas turbine units.

For reciprocating gas-fired engines, the most effective NO_x control measures are those that change the air-fuel ratio. Thus, changes in engine torque, speed, intake air temperature, etc., that in turn increase the air-fuel ratio, may all result in lower NO_x emissions. Exhaust gas recirculation may also be effective in lowering NO_x emissions although, as with turbines, there are practical limits because of the large quantities of exhaust gas that must be cooled. Available data suggest that other NO_x control measures, including water and steam injection, have only limited application to reciprocating gas-fired engines.

Emission factors for natural-gas-fired pipeline compressor engines are presented in Table 3.3.2-1.

Table 3.3.2-1. EMISSION FACTORS FOR HEAVY-DUTY, NATURAL-GAS-FIRED PIPELINE COMPRESSOR ENGINES[a]

EMISSION FACTOR RATING: A

	Nitrogen oxides (as NO_2)[b]	Carbon monoxide	Hydrocarbons (as C)[c]	Sulfur dioxide[d]	Particulate[e]
Reciprocating engines					
lb/10^3 hp-hr	24	3.1	9.7	0.004	NA
g/hp-hr	11	1.4	4.4	0.002	NA
g/kW-hr	15	1.9	5.9	0.003	NA
lb/10^6 scf[f]	3,400	430	1,400	0.6	NA
kg/10^6 $\underline{N}m^3$[f]	55,400	7,020	21,800	9.2	NA
Gas turbines					
lb/10^3 hp-hr	2.9	1.1	0.2	0.004	NA
g/hp-hr	1.3	0.5	0.1	0.002	NA
g/kW-hr	1.7	0.7	0.1	0.003	NA
lb/10^6 scf[g]	300	120	23	0.6	NA
kg/10^6 $\underline{N}m^3$[g]	4,700	1,940	280	9.2	NA

[a] All factors based on References 2 and 3.

[b] These factors are for compressor engines operated at rated load. In general, NO_x emissions will increase with increasing load and intake (manifold) air temperature and decrease with increasing air-fuel ratios (excess air rates) and absolute humidity. Quantitative estimates of the effects of these variables are presented in Reference 2.

[c] These factors represent total hydrocarbons. Nonmethane hydrocarbons are estimated to make up to 5 to 10 percent of these totals, on the average.

[d] Based on an assumed sulfur content of pipeline gas of 2000 gr/10^6 scf (4600 g/$\underline{N}m^3$). If pipeline quality natural gas is not fired, a material balance should be performed to determine SO_2 emissions based on the actual sulfur content.

[e] Not available from existing data.

[f] These factors are calculated from the above factors for reciprocating engines assuming a heating value of 1050 Btu/scf (9350 kcal/$\underline{N}m^3$) for natural gas and an average fuel consumption of 7500 Btu/hp-hr (2530 kcal/kW-hr).

[g] These factors are calculated from the above factors for gas turbines assuming a heating value of 1,050 Btu/scf (9,350 kcal/$\underline{N}m^3$) of natural gas and an average fuel consumption of 10,000 Btu/hp-hr (3,380 kcal/kW-hr).

References for Section 3.3.2

1. Standard Support Document and Environmental Impact Statement - Stationary Reciprocating Internal Combustion Engines. Aerotherm/Acurex Corp., Mountain View, Calif. Prepared for Environmental Protection Agency, Research Triangle Park, N.C. under Contract No. 68-02-1318, Task Order No. 7, November 1974.

2. Urban, C.M. and K.J. Springer. Study of Exhaust Emissions from Natural Gas Pipeline Compressor Engines. Southwest Research Institute, San Antonio, Texas. Prepared for American Gas Association, Arlington, Va. February 1975.

3. Dietzmann, H.E. and K.J. Springer. Exhaust Emissions from Piston and Gas Turbine Engines Used in Natural Gas Transmission. Southwest Research Institute, San Antonio, Texas. Prepared for American Gas Association, Arlington, Va. January 1974.

3.3.3 Gasoline and Diesel Industrial Engines

by David S. Kircher

3.3.3-1 General – This engine category covers a wide variety of industrial applications of both gasoline and diesel internal combustion power plants, such as fork lift trucks, mobile refrigeration units, generators, pumps, and portable well-drilling equipment. The rated power of these engines covers a rather substantial range–from less than 15 kW to 186 kW (20 to 250 hp) for gasoline engines and from 34 kW to 447 kW (45 to 600 hp) for diesel engines. Understandably, substantial differences in both annual usage (hours per year) and engine duty cycles also exist. It was necessary, therefore, to make reasonable assumptions concerning usage in order to formulate emission factors.[1]

3.3.3-2 Emissions – Once reasonable usage and duty cycles for this category were ascertained, emission values from each of the test engines [1] were aggregated (on the basis of nationwide engine population statistics) to arrive at the factors presented in Table 3.3.3-1. Because of their aggregate nature, data contained in this table must be applied to a population of industrial engines rather than to an individual power plant.

The best method for calculating emissions is on the basis of "brake specific" emission factors (g/kWh or lb/hphr). Emissions are calculated by taking the product of the brake specific emission factor, the usage in hours (that is, hours per year or hours per day), the power available (rated power), and the load factor (the power actually used divided by the power available).

Table 3.3.3-1. EMISSION FACTORS FOR GASOLINE- AND DIESEL-POWERED INDUSTRIAL EQUIPMENT
EMISSION FACTOR RATING: C

Pollutant[a]	Engine category[b]	
	Gasoline	Diesel
Carbon monoxide		
g/hr	5700.	197.
lb/hr	12.6	0.434
g/kWh	267.	4.06
g/hphr	199.	3.03
kg/10^3 liter	472.	12.2
lb/10^3 gal	3940.	102.
Exhaust hydrocarbons		
g/hr	191.	72.8
lb/hr	0.421	0.160
g/kWh	8.95	1.50
g/hphr	6.68	1.12
kg/10^3 liter	15.8	4.49
lb/10^3 gal	132.	37.5
Evaporative hydrocarbons		
g/hr	62.0	–
lb/hr	0.137	–
Crankcase hydrocarbons		
g/hr	38.3	–
lb/hr	0.084	–

Table 3.3.3-1. (continued). EMISSION FACTORS FOR GASOLINE- AND DIESEL-POWERED INDUSTRIAL EQUIPMENT
EMISSION FACTOR RATING: C

Pollutant[a]	Engine category[b]	
	Gasoline	Diesel
Nitrogen oxides		
g/hr	148.	910.
lb/hr	0.326	2.01
g/kWh	6.92	18.8
g/hphr	5.16	14.0
kg/10^3 liter	12.2	56.2
lb/10^3 gal	102.	469.
Aldehydes		
g/hr	6.33	13.7
lb/hr	0.014	0.030
g/kWh	0.30	0.28
g/hphr	0.22	0.21
kg/10^3 liter	0.522	0.84
lb/10^3 gal	4.36	7.04
Sulfur oxides		
g/hr	7.67	60.5
lb/hr	0.017	0.133
g/kWh	0.359	1.25
g/hphr	0.268	0.931
kg/10^3 liter	0.636	3.74
lb/10^3 gal	5.31	31.2
Particulate		
g/hr	9.33	65.0
lb/hr	0.021	0.143
g/kWh	0.439	1.34
g/hphr	0.327	1.00
kg/10^3 liter	0.775	4.01
lb/10^3 gal	6.47	33.5

[a] References 1 and 2.

[b] As discussed in the text, the engines used to determine the results in this table cover a wide range of uses and power. The listed values do not, however, necessarily apply to some very large stationary diesel engines.

References for Section 3.3.3

1. Hare, C. T. and K. J. Springer. Exhaust Emissions from Uncontrolled Vehicles and Related Equipment Using Internal Combustion Engines. Final Report. Part 5: Heavy-Duty Farm, Construction, and Industrial Engines. Southwest Research Institute. San Antonio, Texas. Prepared for Environmental Protection Agency, Research Triangle Park, N.C., under Contract No. EHS 70-108. October 1973. 105 p.

2. Hare, C. T. Letter to C. C. Masser of the Environmental Protection Agency concerning fuel-based emission rates for farm, construction, and industrial engines. San Antonio, Tex. January 14, 1974.

4. EVAPORATION LOSS SOURCES

Evaporation losses include the organic solvents emitted from dry-cleaning plants and surface-coating operations as well as the volatile matter in petroleum products. This chapter presents the hydrocarbon emissions from these sources, including liquid petroleum storage and marketing. Where possible, the effect of controls to reduce the emissions of organic compounds has been shown.

4.1 DRY CLEANING

by Susan Sercer

4.1.1 General[1,2]

Dry cleaning involves the cleaning of fabrics with non-aqueous organic solvents. The dry cleaning process requires three steps: (1) washing the fabric in solvent, (2) spinning to extract excess solvent, and (3) drying by tumbling in a hot airstream.

Two general types of cleaning fluids are used in the industry: petroleum solvents and synthetic solvents. Petroleum solvents, such as Stoddard or 140-F, are inexpensive, combustible hydrocarbon mixtures similar to kerosene. Operations using petroleum solvents are known as petroleum plants. Synthetic solvents are nonflammable but more expensive halogenated hydrocarbons. Perchloroethylene and trichlorotrifluoroethane are the two synthetic dry cleaning solvents presently in use. Operations using these synthetic solvents are called "perc" plants and fluorocarbon plants, respectively.

There are two basic types of dry cleaning machines: transfer and dry-to-dry. Transfer machines accomplish washing and drying in separate machines. Usually the washer extracts excess solvent from the clothes before they are transferred to the dryer, however, some older petroleum plants have separate extractors for this purpose. Dry-to-dry machines are single units that perform all of the washing, extraction, and drying operations. All petroleum solvent machines are the transfer type, but synthetic solvent plants can be either type.

The dry cleaning industry can be divided into three sectors: coin-operated facilities, commercial operations, and industrial cleaners. Coin-operated facilities are usually part of a laundry and supply "self-service" type dry cleaning for consumers. Only synthetic solvents are used in coin-operated dry cleaning machines. Such machines are small, with a capacity of 8 to 25 lb (3.6 to 11.5 kg) of clothing.

Commercial operations, such as small neighborhood or franchise dry cleaning shops, clean soiled apparel for the consumer. Generally, perchloroethylene and petroleum solvents are used in commercial operations. A typical "perc" plant operates a 30 to 60 lb (14 to 27 kg) capacity washer/extractor and an equivalent size reclaiming dryer.

Industrial cleaners are larger dry cleaning plants which supply rental service of uniforms, mats, mops, etc., to businesses or industries. Although petroleum solvents are used extensively, perchloroethylene is used by approximately 50% of the industrial dry cleaning establishments. A typical large industrial cleaner has a 500 lb (230 kg) capacity washer/extractor and three to six 100 lb (38 kg) capacity dryers.

A typical perc plant is shown in Figure 4.1-1. Although one solvent tank may be used, the typical perc plant uses two tanks for washing. One tank contains pure solvent; the other tank contains "charged" solvent—used solvent to which small amounts of detergent have been added to aid in cleaning. Generally, clothes are cleaned in charged solvent and rinsed in pure solvent. A water bath may also be used.

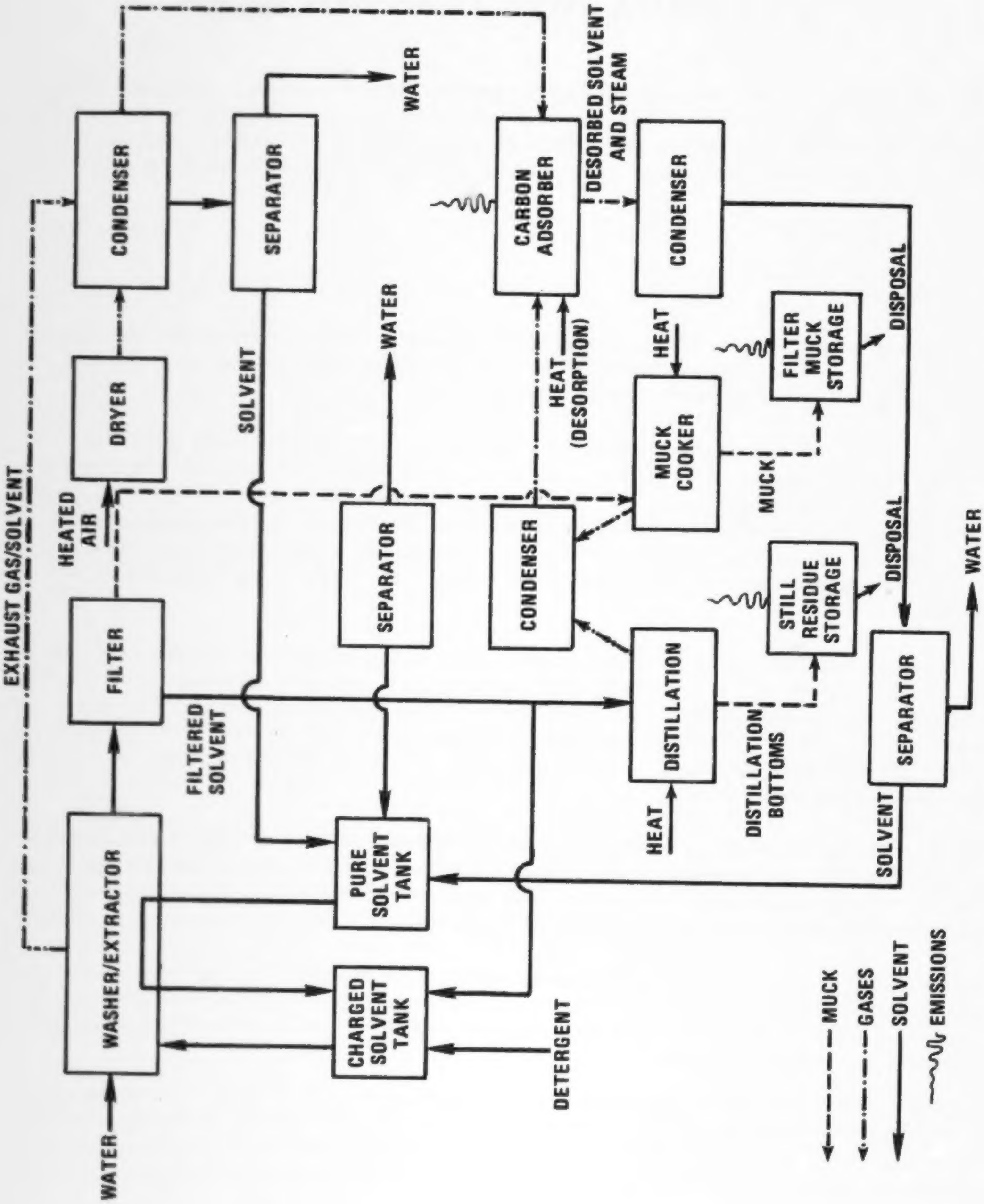

WATER
WASHER/EXTRACTOR
CHARGED SOLVENT TANK
PURE SOLVENT TANK
DETERGENT
EXHAUST GAS/SOLVENT
FILTER
FILTERED SOLVENT
HEATED AIR
DRYER
CONDENSER
SEPARATOR
WATER
SOLVENT
SEPARATOR
WATER
CONDENSER
CARBON ADSORBER
HEAT (DESORPTION)
DESORBED SOLVENT AND STEAM
CONDENSER
DISTILLATION
HEAT
DISTILLATION BOTTOMS
MUCK COOKER
HEAT
MUCK
FILTER MUCK STORAGE
DISPOSAL
STILL RESIDUE STORAGE
DISPOSAL
SEPARATOR
SOLVENT
WATER
MUCK
GASES
SOLVENT
EMISSIONS

Figure 4.1-1. Perchloroethylene dry cleaning plant flow diagram.

After the clothes have been washed, the used solvent is filtered, and part of the filtered solvent is returned to the charged solvent tank for washing the next load. The remaining solvent is then distilled to remove oils, fats, greases, etc., and returned to the pure solvent tank. The resulting distillation bottoms are typically stored on the premises until disposed of. The filter cake and collected solids (muck) are usually removed from the filter once a day. Before disposal, the muck may be "cooked" to recover additional solvent. Still and muck cooker vapors are vented to a condenser and separator where more solvent is reclaimed. In many perc plants, the condenser off-gases are vented to a carbon adsorption unit for additional solvent recovery.

After washing, the clothes are transferred to the dryer where they are tumbled in a heated airstream. Exhaust gases from the dryer, along with a small amount of exhaust gases from the washer/extractor, are vented to a water-cooled condenser and water separator. Recovered solvent is returned to the pure solvent storage tank. In 30-50 percent of the perc plants, the condenser off-gases are vented to a carbon adsorption unit for additional solvent recovery. To reclaim this solvent, the unit must be periodically desorbed with steam—typically at the end of each day. Desorbed solvent and water are condensed and separated; recovered solvent is returned to the pure solvent tank.

A petroleum plant would differ from Figure 4.1-1 chiefly in that there would be no recovery of solvent from the washer and dryer and no muck cooker. A fluorocarbon plant would differ in that a nonvented refrigeration system would be used in place of a carbon adsorption unit. Another difference would be that a typical fluorocarbon plant would use a cartridge filter which is drained and disposed of after several hundred cycles.

Emissions and Controls[1,2,3]

The solvent material itself is the primary emission of concern from dry cleaning operations. Solvent is given off by the washer, dryer, solvent still, muck cooker, still residue and filter muck storage areas, as well as leaky pipes, flanges, and pumps.

Petroleum plants have generally not employed solvent recovery because of the low cost of petroleum solvents and the fire hazards associated with collecting vapors. Some emission control, however, can be obtained by maintaining all equipment in good condition (e.g., preventing lint accumulation, preventing solvent leakage, etc.) and by using good operating practices (e.g., not overloading machinery). Both carbon adsorption and incineration appear to be technically feasible controls for petroleum plants, but costs are high.

Solvent recovery is necessary in perc plants due to the higher cost of perchloroethylene. As shown in Figure 4.1-1, recovery is effected on the washer, dryer, still, and muck cooker through the use of condensers, water/solvent separators, and carbon adsorption units. Periodically (typically once a day), solvent collected in the carbon adsorption unit is desorbed with steam, condensed, separated from the condensed water, and returned to the pure solvent storage tank. Residual solvent emitted from treated distillation bottoms and muck is not recovered. As in petroleum plants, good emission control can be obtained by good housekeeping practices (maintaining all equipment in good condition and using good operating practices).

All fluorocarbon machines are of the dry-to-dry variety to conserve solvent vapor, and all are closed systems with built-in solvent recovery. High emissions can occur, however, as a result of poor maintenance and operation of equipment. Refrigeration systems are installed on newer machines to recover solvent from the washer/dryer exhaust gases.

Emission factors for dry cleaning operations are presented in Table 4.1-1.

Table 4.1-1. SOLVENT LOSS EMISSION FACTORS FOR DRY CLEANING OPERATIONS
EMISSION FACTOR RATING: B

Solvent type (Process used)	Source	Emission rate[a] Typical systems lb/100 lb (kg/100 kg)	Emission rate[a] Well-controlled system lb/100 lb (kg/100 kg)
Petroleum (transfer process)	washer/dryer[f]	18	2[b]
	filter disposal		
	uncooked (drained)	5	
	centrifuged		0.5 - 1
	still residue disposal	2	0.5 - 1
	miscellaneous[c]	3	1
Perchloroethylene (transfer process)	washer/dryer/still/muck cooker	8[d]	0.3[b]
	filter disposal		
	uncooked muck	14	
	cooked muck	1.3	0.5 - 1.3
	cartridge filter	1.1	0.5 - 1.1
	still residue disposal	1.6	0.5 - 1.6
	miscellaneous[c]	1.5	1
Trichlorotrifluoroethane (dry-to-dry process)	washer/dryer/still[e]	0	0
	cartridge filter disposal	1	1
	still residue disposal	0.5	0.5
	miscellaneous[c]	1 - 3	1 - 3

[a] Units are in terms of weight of solvent per weight of clothes cleaned (capacity x loads). Emissions may be estimated on an alternative basis by determining the amount of solvent consumed. Assuming that all solvent input to dry cleaning operations is eventually evaporated to the atmosphere, an emission factor of 2000 lb/ton of solvent consumed can be applied. All emission factors are based on References 1, 2 and 3.

[b] Emissions from the washer, dryer, still, and muck cooker are collectively passed through a carbon adsorber.

[c] Miscellaneous sources include fugitive emissions from flanges, pumps, pipes, storage tanks, fixed losses (for example, opening and closing the dryer), etc.

[d] Uncontrolled emissions from the washer, dryer, still, and muck cooker average about 8 lb/100 lb (8 kg/100 kg). Roughly 15% of the solvent emitted comes from the washer, 75% from the dryer, and 5% from both the still and the muck cooker.

[e] Emission factors are based on the typical refrigeration system installed in fluorocarbon plants.

[f] Different materials in the wash retain varying amounts of solvent (synthetic: 10 kg/100 kg, cotton: 20 kg/100 kg, leather: 40 kg/100 kg).

References for Section 4.1

1. Study to Support New Source Performance Standards for the Dry Cleaning Industry, EPA Contract 68-02-1412, Task Order No. 4, prepared by TRW Inc., Vienna, Virginia, May 7, 1976. Kleeberg, Charles, EPA, Office of Air Quality Planning and Standards.

2. Standard Support and Environmental Impact Statement for the Dry Cleaning Industry. Durham, North Carolina. June 28, 1976.

3. Control of Volatile Organic Emissions from Dry Cleaning Operations (Draft Document), Durham, North Carolina. April 15, 1977.

4.2 SURFACE COATING

4.2.1 Process Description[1,2]

Surface-coating operations primarily involve the application of paint, varnish, lacquer, or paint primer for decorative or protective purposes. This is accomplished by brushing, rolling, spraying, flow coating, and dipping. Some of the industries involved in surface-coating operations are automobile assemblies, aircraft companies, container manufacturers, furniture manufacturers, appliance manufacturers, job enamelers, automobile re-painters, and plastic products manufacturers.

4.2.2 Emissions and Controls[3]

Emissions of hydrocarbons occur in surface-coating operations because of the evaporation of the paint vehicles, thinners, and solvents used to facilitate the application of the coatings. The major factor affecting these emissions is the amount of volatile matter contained in the coating. The volatile portion of most common surface coatings averages approximately 50 percent, and most, if not all, of this is emitted during the application and drying of the coating. The compounds released include aliphatic and aromatic hydrocarbons, alcohols, ketones, esters, alkyl and aryl hydrocarbon solvents, and mineral spirits. Table 4.2-1 presents emission factors for surface-coating operations.

Control of the gaseous emissions can be accomplished by the use of adsorbers (activated carbon) or afterburners. The collection efficiency of activated carbon has been reported at 90 percent or greater. Water curtains or filler pads have little or no effect on escaping solvent vapors; they are widely used, however, to stop paint particulate emissions.

Table 4.2-1. GASEOUS HYDROCARBON EMISSION FACTORS FOR SURFACE-COATING APPLICATIONS[a]
EMISSION FACTOR RATING: B

Type of coating	Emissions[b]	
	lb/ton	kg/MT
Paint	1120	560
Varnish and shellac	1000	500
Lacquer	1540	770
Enamel	840	420
Primer (zinc chromate)	1320	660

[a] Reference 1.

[b] Reported as undefined hydrocarbons, usually organic solvents, both aryl and alkyl. Paints weigh 10 to 15 pounds per gallon (1.2 to 1.9 kilograms per liter); varnishes weigh about 7 pounds per gallon (0.84 kilogram per liter).

References for Section 4.2

1. Weiss, S.F. Surface Coating Operations. In: Air Pollution Engineering Manual, Danielson, J.A. (ed.). U.S. DHEW, PHS, National Center for Air Pollution Control. Cincinnati, Ohio. Publication Number 999-AP-40. p.387-390.

2. Control Techniques for Hydrocarbon and Organic Gases From Stationary Sources. U.S. DHEW, PHS, EHS, National Air Pollution Control Administration. Washington, D.C. Publication Number AP-68. October 1969. Chapter 7.6.

3. Air Pollutant Emission Factors. Final Report. Resources Research, Inc. Reston, Va. Prepared for National Air Pollution Control Administration, Durham, N.C., under Contract Number CPA-22-69-119. April 1970.

4.3 STORAGE OF PETROLEUM LIQUIDS[1]

by Charles C. Masser

Fundamentally, the petroleum industry consists of three operations: (1) petroleum production and transportation, (2) petroleum refining, and (3) transportation and marketing of finished petroleum products. All three operations require some type of storage for petroleum liquids. Storage tanks for both crude and finished products can be sources of evaporative emissions. Figure 4.3-1 presents a schematic of the petroleum industry and its points of emissions from storage operations.

4.3.1 Process Description

Four basic tank designs are used for petroleum storage vessels: fixed roof, floating roof (open type and covered type), variable vapor space, and pressure (low and high).

4.3.1.1 Fixed Roof Tanks[2] - The minimum accepted standard for storage of volatile liquids is the fixed roof tank (Figure 4.3-2). It is usually the least expensive tank design to construct. Fixed roof tanks basically consist of a cylindrical steel shell topped by a coned roof having a minimum slope of 3/4 inch in 12 inches. Fixed roof tanks are generally equipped with a pressure/vacuum vent designed to contain minor vapor volume changes. For large fixed roof tanks, the recommended maximum operating pressure/vacuum is +0.03 psig/-0.03 psig (+2.1 g/cm^2/-2.1 g/cm^2).

4.3.1.2 Floating Roof Tanks[3] - Floating roof tanks reduce evaporative storage losses by minimizing vapor spaces. The tank consists of a welded or riveted cylindrical steel wall, equipped with a deck or roof which is free to float on the surface of the stored liquid. The roof then rises and falls according to the depth of stored liquid. To ensure that the liquid surface is completely covered, the roof is equipped with a sliding seal which fits against the tank wall. Sliding seals are also provided at support columns and at all other points where tank appurtenances pass through the floating roof.

Until recent years, the most commonly used floating roof tank was the conventional open-type tank. The open-type floating roof tank exposes the roof deck to the weather; provisions must be made for rain water drainage, snow removal, and sliding seal dirt protection. Floating roof decks are of three general types: pan, pontoon, and double deck. The pan-type roof consists of a flat metal plate with a vertical rim and sufficient stiffening braces to maintain rigidity (Figure 4.3-3). The single metal plate roof in contact with the liquid readily conducts solar heat, resulting in higher vaporization losses than other floating roof decks. The roof is equipped with automatic vents for pressure and vacuum release. The pontoon roof is a pan-type floating roof with pontoon sections added to the top of the deck around the rim. The pontoons are arranged to provide floating stability under heavy loads of water and snow. Evaporation losses due to solar heating are about the same as for pan-type roofs. Pressure/vacuum vents are required on pontoon roof tanks. The double deck roof is similar to a pan-type floating roof, but consists of a hollow double deck covering the entire surface of the roof (Figure 4.3-4). The double deck adds rigidity, and the dead air space between the upper and lower deck provides significant insulation from solar heating. Pressure/vacuum vents are also required.

The covered-type floating roof tank is essentially a fixed-roof tank with a floating roof deck inside the tank (Figure 4.3-5). The American Petroleum Institute has designated the term "covered floating" roof to describe a fixed roof tank with an internal steel pan-type floating roof. The term "internal floating cover" has been chosen by the API to describe internal covers constructed of materials other than steel. Floating roofs and covers can be installed inside existing fixed roof tanks. The fixed roof protects the floating roof from the weather, and no provision is necessary for rain or snow removal, or for seal

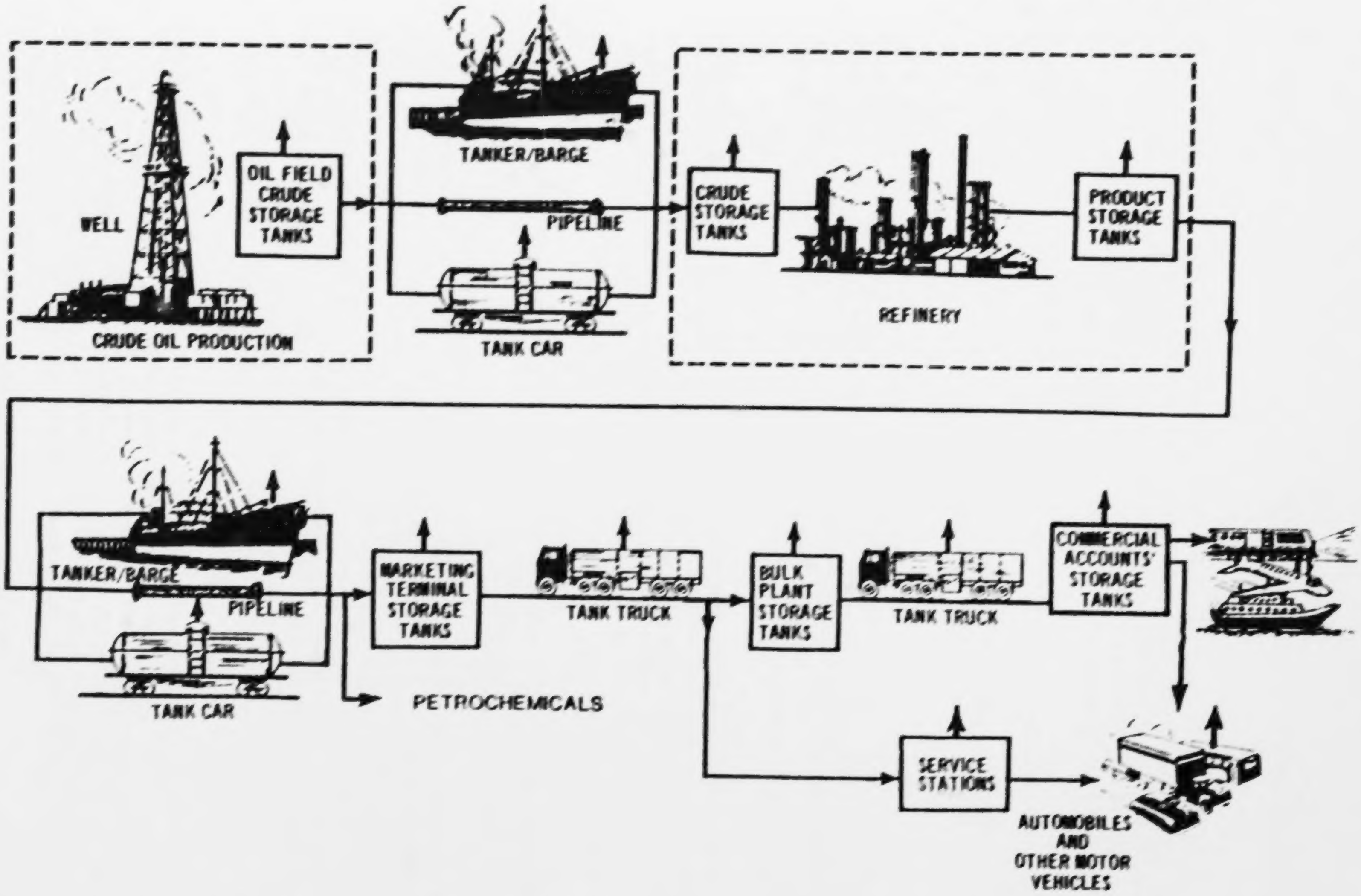

WELL
OIL FIELD CRUDE STORAGE TANKS
CRUDE OIL PRODUCTION
TANKER/BARGE
PIPELINE
TANK CAR
CRUDE STORAGE TANKS
REFINERY
PRODUCT STORAGE TANKS
TANKER/BARGE
PIPELINE
TANK CAR
MARKETING TERMINAL STORAGE TANKS
PETROCHEMICALS
TANK TRUCK
BULK PLANT STORAGE TANKS
TANK TRUCK
COMMERCIAL ACCOUNTS' STORAGE TANKS
SERVICE STATIONS
AUTOMOBILES AND OTHER MOTOR VEHICLES

Figure 4.3-1. Flowsheet of petroleum production, refining, and distribution systems. (Sources of organic evaporative emissions are indicated by vertical arrows.)

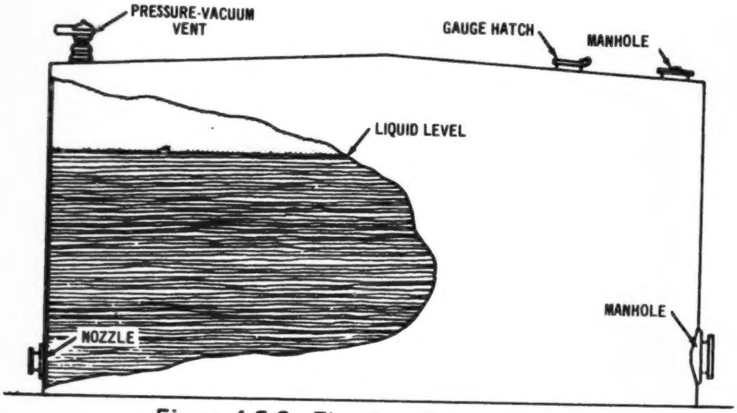

PRESSURE-VACUUM VENT
GAUGE HATCH
MANHOLE
LIQUID LEVEL
MANHOLE
NOZZLE

Figure 4.3-2. Fixed roof storage tank.

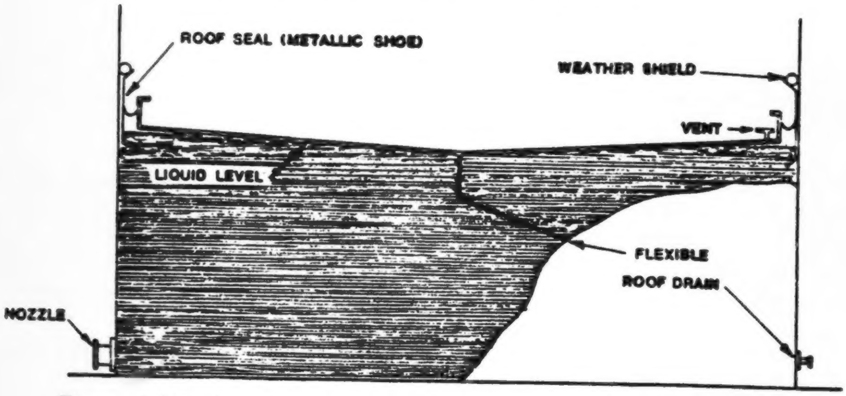

ROOF SEAL (METALLIC SHOE)
WEATHER SHIELD
VENT
LIQUID LEVEL
FLEXIBLE
ROOF DRAIN
NOZZLE

Figure 4.3-3. Pan-type floating roof storage tank (metallic seals).

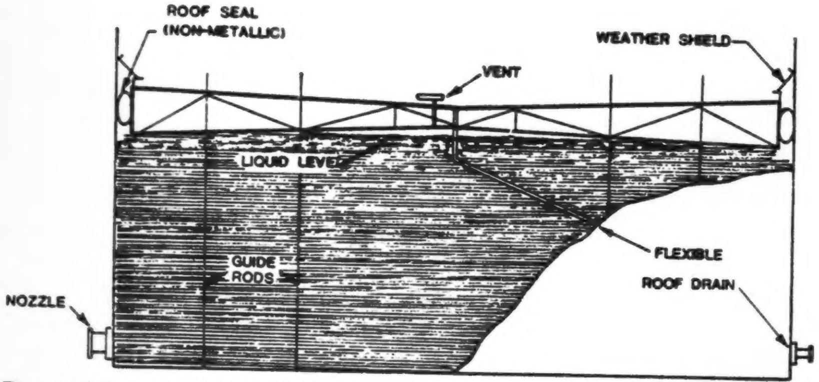

ROOF SEAL (NON-METALLIC)
WEATHER SHIELD
VENT
LIQUID LEVEL
FLEXIBLE
GUIDE RODS
ROOF DRAIN
NOZZLE

Figure 4.3-4. Double deck floating roof storage tank (non-metallic seals).

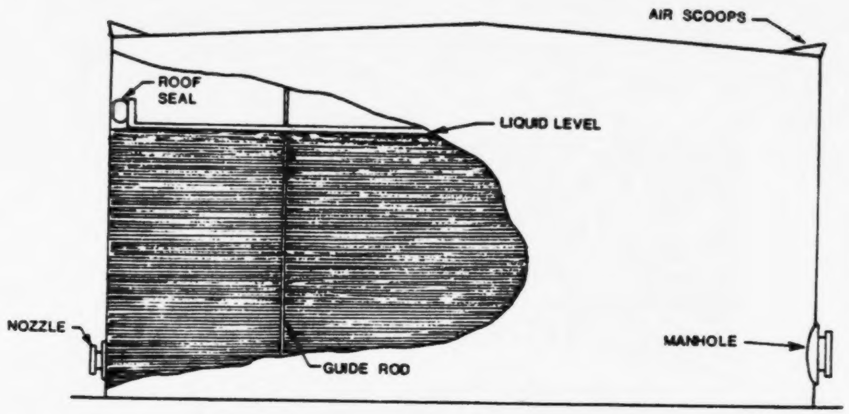

AIR SCOOPS
ROOF SEAL
LIQUID LEVEL
NOZZLE
GUIDE ROD
MANHOLE

Figure 4.3-5. Covered floating roof storage tank.

protection. Antirotational guides must be provided to maintain roof alignment, and the space between the fixed and floating roofs must be vented to prevent the possible formation of a flammable mixture.

4.3.1.3 Variable Vapor Space Tanks[4] - Variable vapor space tanks are equipped with expandable vapor reservoirs to accommodate vapor volume fluctuations attributable to temperature and barometric pressure changes. Although variable vapor space tanks are sometimes used independently, they are normally connected to the vapor spaces of one or more fixed roof tanks. The two most common types of variable vapor space tanks are lifter roof tanks and flexible diaphragm tanks.

Lifter roof tanks have a telescoping roof that fits loosely around the outside of the main tank wall. The space between the roof and the wall is closed by either a wet seal, which consists of a trough filled with liquid, or a dry seal, which employs a flexible coated fabric in place of the trough (Figure 4.3-6).

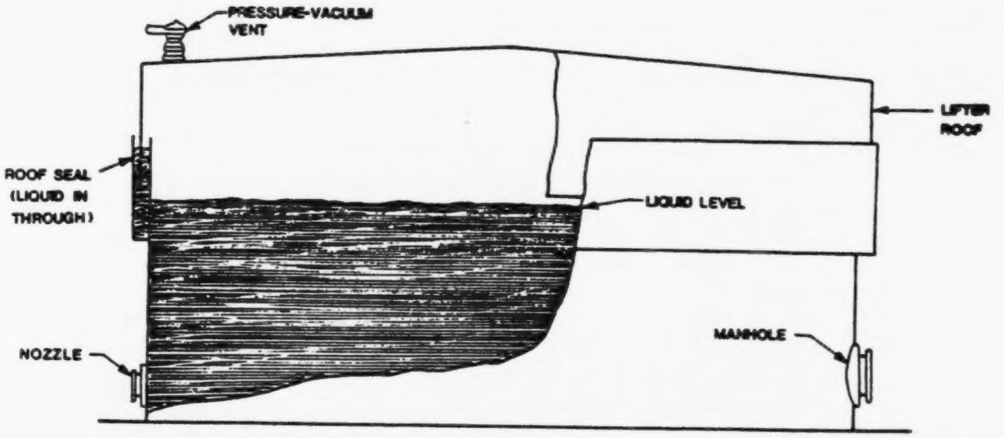

PRESSURE-VACUUM VENT
LIFTER ROOF
ROOF SEAL (LIQUID IN THROUGH)
LIQUID LEVEL
NOZZLE
MANHOLE

Figure 4.3-6. Lifter roof storage tank (wet seal).

Flexible diaphragm tanks utilize flexible membranes to provide the expandable volume. They may be separate gasholder type units, or integral units mounted atop fixed roof tanks (Figure 4.3-7).

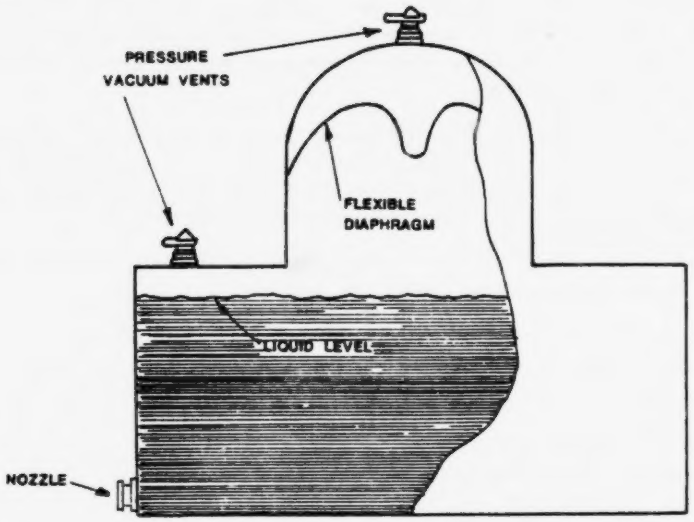


Figure 4.3-7. Flexible diaphragm tank (integral unit).

4.3.1.4 **Pressure Tanks**[5] - Pressure tanks are designed to withstand relatively large pressure variations without incurring a loss. They are generally used for storage of high volatility stocks, and they are constructed in many sizes and shapes, depending on the operating range. The noded spheroid and noded hemispheroid shapes are generally used as low-pressure tanks (17 to 30 psia or 12 to 21 mg/m^2), while the horizontal cylinder and spheroid shapes are generally used as high-pressure tanks (up to 265 psia or 186 mg/m^2).

4.3.2 Emissions and Controls

There are six sources of emissions from petroleum liquids in storage: fixed roof breathing losses, fixed roof working losses, floating roof standing storage losses, floating roof withdrawal losses, variable vapor space filling losses, and pressure tank losses.[6]

Fixed roof breathing losses consist of vapor expelled from a tank because of the thermal expansion of existing vapors, vapor expansion caused by barometric pressure changes, and/or an increase in the amount of vapor due to added vaporization in the absence of a liquid-level change.

Fixed roof working losses consist of vapor expelled from a tank as a result of filling and emptying operations. Filling loss is the result of vapor displacement by the input of liquid. Emptying loss is the expulsion of vapors subsequent to product withdrawal, and is attributable to vapor growth as the newly inhaled air is saturated with hydrocarbons.

Floating roof standing storage losses result from causes other than breathing or changes in liquid level. The largest potential source of this loss is attributable to an improper fit of the seal and shoe to the shell, which exposes some liquid surface to the atmosphere. A small amount of vapor may escape between the flexible membrane seal and the roof.

Floating roof withdrawal losses result from evaporation of stock which wets the tank wall as the roof descends during emptying operations. This loss is small in comparison to other types of losses.

Variable vapor space filling losses result when vapor is displaced by the liquid input during filling operations. Since the variable vapor space tank has an expandable vapor storage capacity, this loss is not as large as the filling loss associated with fixed roof tanks. Loss of vapor occurs only when the vapor storage capacity of the tank is exceeded.

Pressure tank losses occur when the pressure inside the tank exceeds the design pressure of the tank, which results in relief vent opening. This happens only when the tank is filled improperly, or when abnormal vapor expansion occurs. These are not regularly occurring events, and pressure tanks are not a significant source of loss under normal operating conditions.

The total amount of evaporation loss from storage tanks depends upon the rate of loss and the period of time involved. Factors affecting the rate of loss include:

1. True vapor pressure of the liquid stored.
2. Temperature changes in the tank.
3. Height of the vapor space (tank outage).
4. Tank diameter.
5. Schedule of tank filling and emptying.
6. Mechanical condition of tank and seals.
7. Type of tank and type of paint applied to outer surface.

The American Petroleum Institute has developed empirical formulae, based on field testing, that correlate evaporative losses with the above factors and other specific storage factors.

4.3.2.1 Fixed Roof Tanks[2,7] - Fixed roof breathing losses can be estimated from:

$$L_B = 2.21 \times 10^{-4} M \left[\frac{P}{14.7 - P}\right]^{0.68} D^{1.73} H^{0.51} \Delta T^{0.50} F_p C K_c \qquad (1)$$

where: L_B = Fixed roof breathing loss (lb/day).

M = Molecular weight of vapor in storage tank (lb/lb mole). (see Table 4.3-1).

P = True vapor pressure at bulk liquid conditions (psia); see Figures 4.3-8, 4.3-9, or Table 4.3-1.

D = Tank diameter (ft).

H = Average vapor space height, including roof volume correction (ft); see note (1).

ΔT = Average ambient temperature change from day to night (°F).

F_p = Paint factor (dimensionless); see Table 4.3-2.

C = Adjustment factor for small diameter tanks (dimensionless); see Figure 4.3-10.

K_c = Crude oil factor (dimensionless); see note (2).

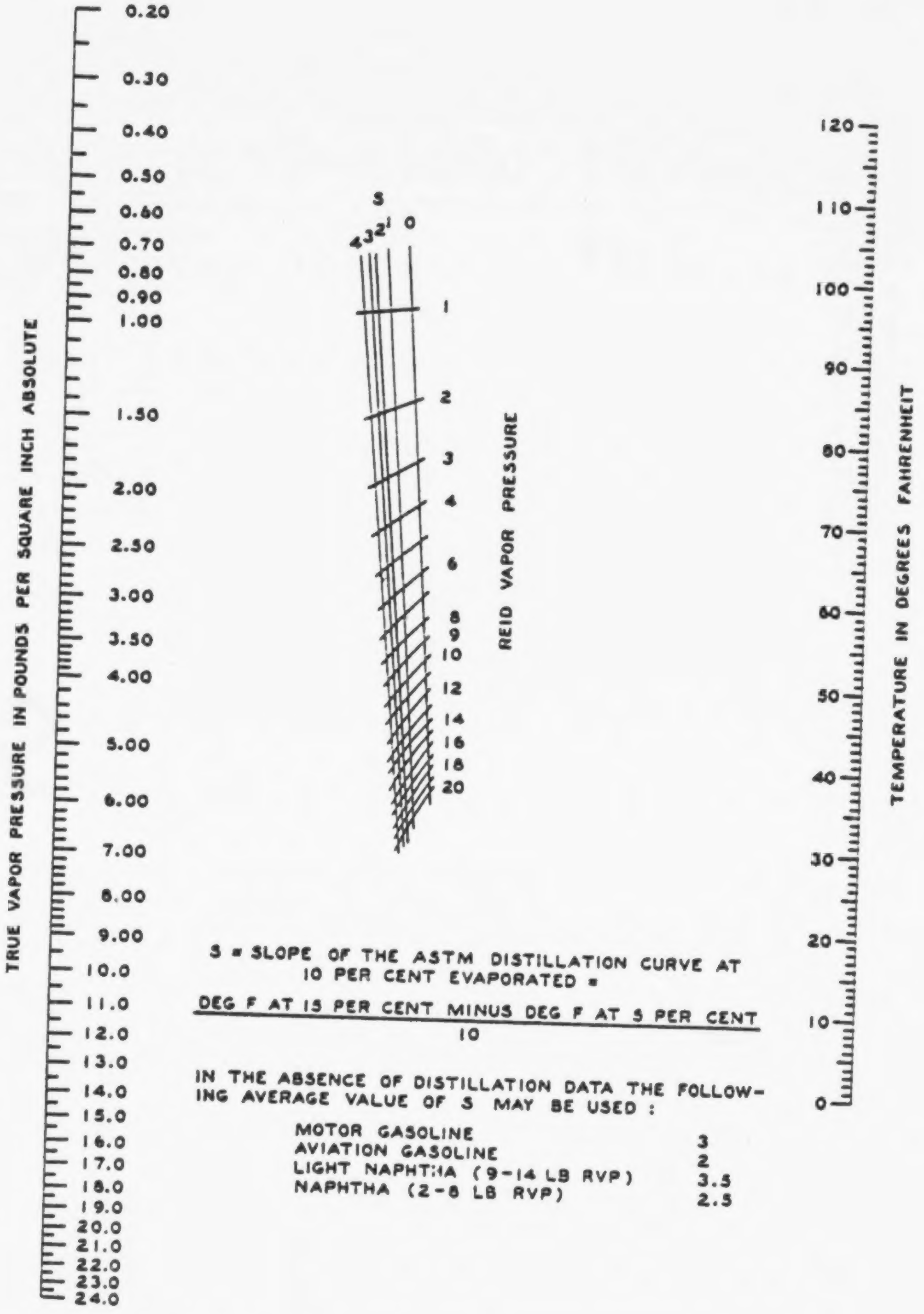
Note: (1) The vapor space in a cone roof is equivalent in volume to a cylinder which has the same base diameter as the cone and is one-third the height of the cone.

(2) K_c = (0.65) for crude oil, K_c = (1.0) for gasoline and all other liquids.

API reports that calculated breathing loss from Equation (1) may deviate in the order of ± 10 percent from actual breathing loss.

Table 4.3-1. PHYSICAL PROPERTIES OF HYDROCARBONS [7,9]

Hydrocarbon	Vapor molecular weight @ 60°F	Product density (d), lb/gal @ 60°F	Condensed vapor density (w), lb/gal @ 60°F	Vapor pressure in psia at:						
				40°F	50°F	60°F	70°F	80°F	90°F	100°F
Fuels										
Gasoline RVP 13	62	5.6	4.9	4.7	5.7	6.9	8.3	9.9	11.7	13.8
Gasoline RVP 10	66	5.6	5.1	3.4	4.2	5.2	6.2	7.4	8.8	10.5
Gasoline RVP 7	68	5.6	5.2	2.3	2.9	3.5	4.3	5.2	6.2	7.4
Crude oil RVP 5	50	7.1	4.5	1.8	2.3	2.8	3.4	4.0	4.8	5.7
Jet naphtha (JP-4)	80	6.4	5.4	0.8	1.0	1.3	1.6	1.9	2.4	2.7
Jet kerosene	130	7.0	6.1	0.0041	0.0060	0.0085	0.011	0.015	0.021	0.029
Distillate fuel No. 2	130	7.1	6.1	0.0031	0.0045	0.0074	0.0090	0.012	0.016	0.022
Residual oil No. 6	190	7.9	6.4	0.00002	0.00003	0.00004	0.00006	0.00009	0.00013	0.00019
Petrochemicals										
Acetone	58	6.6	6.6	1.7	2.2	2.9	3.7	4.7	5.9	7.3
Acrylonitrile	53	6.8	6.8	0.8	1.0	1.4	1.8	2.4	3.1	4.0
Benzene	78	7.4	7.4	0.6	0.9	1.2	1.5	2.0	2.6	3.3
Carbon disulfide	76	10.6	10.6	3.0	3.9	4.8	6.0	7.4	9.2	11.2
Carbon tetrachloride	154	13.4	13.4	0.8	1.1	1.4	1.8	2.3	3.0	3.8
Chloroform	119	12.5	12.5	1.5	1.9	2.5	3.2	4.1	5.2	6.3
Cyclohexane	84	6.5	6.5	0.7	0.9	1.2	1.6	2.1	2.6	3.2
1, 2 - Dichlorethane	99	10.5	10.5	0.6	0.8	1.0	1.4	1.7	2.2	2.8
Ethylacetate	88	7.6	7.6	0.6	0.8	1.1	1.5	1.9	2.5	3.2
Ethyl alcohol	46	6.6	6.6	0.2	0.4	0.6	0.9	1.2	1.7	2.3
Isopropyl alcohol	60	6.6	6.6	0.2	0.3	0.5	0.7	0.9	1.3	1.8
Methyl alcohol	32	6.6	6.6	0.7	1.0	1.4	2.0	2.6	3.5	4.5
Methylene chloride	85	11.1	11.1	3.1	4.3	5.4	6.8	8.7	10.3	13.3
Methyl-ethyl-ketone	72	6.7	6.7	0.7	0.9	1.2	1.5	2.1	2.7	3.3
Methyl-methacrylate	100	7.9	7.9	0.1	0.2	0.3	0.5	0.8	1.1	1.4
1, 1, 1 - Trichloroethane	133	11.2	11.2	0.9	1.2	1.6	2.0	2.6	3.3	4.2
Trichloroethylene	131	12.3	12.3	0.5	0.7	0.9	1.2	1.5	2.0	2.6
Toluene	92	7.3	7.3	0.2	0.2	0.3	0.4	0.6	0.8	1.0
Vinylacetate	86	7.8	7.8	0.7	1.0	1.3	1.7	2.3	3.1	4.0



S = SLOPE OF THE ASTM DISTILLATION CURVE AT 10 PER CENT EVAPORATED =

$$\frac{\text{DEG F AT 15 PER CENT MINUS DEG F AT 5 PER CENT}}{10}$$

IN THE ABSENCE OF DISTILLATION DATA THE FOLLOWING AVERAGE VALUE OF S MAY BE USED :

MOTOR GASOLINE	3
AVIATION GASOLINE	2
LIGHT NAPHTHA (9-14 LB RVP)	3.5
NAPHTHA (2-8 LB RVP)	2.5

Figure 4.3-8. Vapor pressures of gasolines and finished petroleum products.

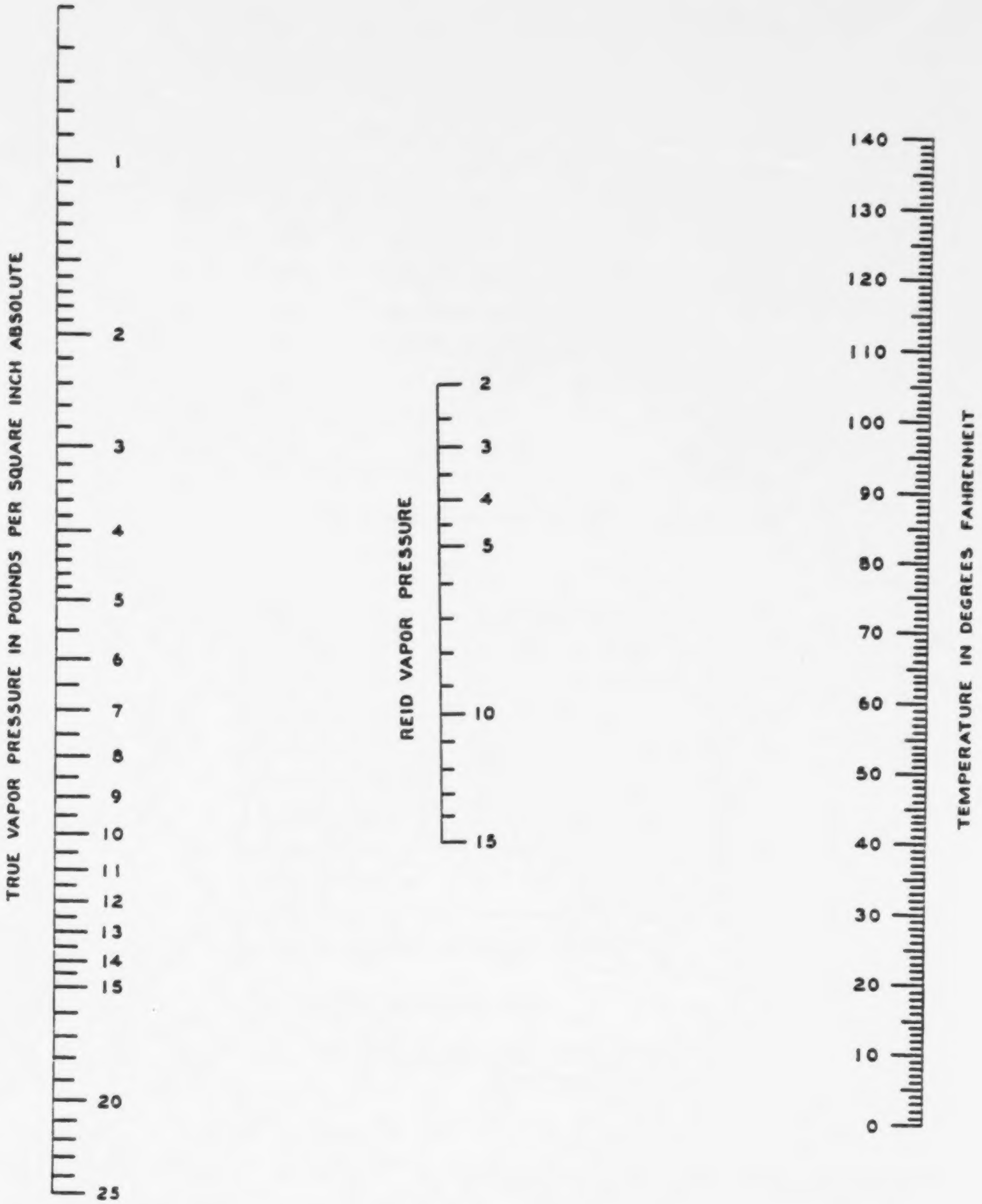


Figure 4.3-9. Vapor pressures of crude oil.

Table 4.3-2. PAINT FACTORS FOR FIXED ROOF TANKS[2]

Tank color		Paint factors (F_p)	
		Paint condition	
Roof	Shell	Good	Poor
White	White	1.00	1.15
Aluminum (specular)	White	1.04	1.18
White	Aluminum (specular)	1.16	1.24
Aluminum (specular)	Aluminum (specular)	1.20	1.29
White	Aluminum (diffuse)	1.30	1.38
Aluminum (diffuse)	Aluminum (diffuse)	1.39	1.46
White	Gray	1.30	1.38
Light gray	Light gray	1.33	1.44[a]
Medium gray	Medium gray	1.40	1.58[a]

[a] Estimated from the ratios of the seven preceding paint factors.

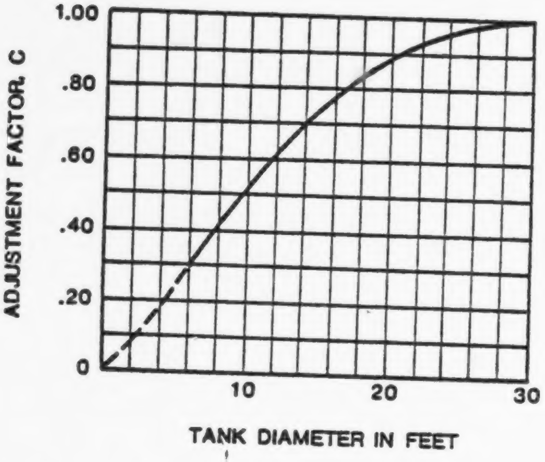


Figure 4.3-10. Adjustment factor (C) for small diameter tanks.

Fixed roof working losses can be estimated from:

$$L_W = 2.40 \times 10^{-2} M P K_N K_c \tag{2}$$

where: L_W = Fixed roof working loss (lb/10^3 gal throughput).

M = Molecular weight of vapor in storage tank (lb/lb mole). see Table 4.3-1.

P = True vapor pressure at bulk liquid conditions (psia); see Figures 4.3-8, 4.3-9, or Table 4.3-1.

K_N = Turnover factor (dimensionless); see Figure 4.3-11.

K_c = Crude oil factor (dimensionless); see note.

Note: K_c = (0.84) for crude oil, K_c = (1.0) for gasoline and all other liquids.

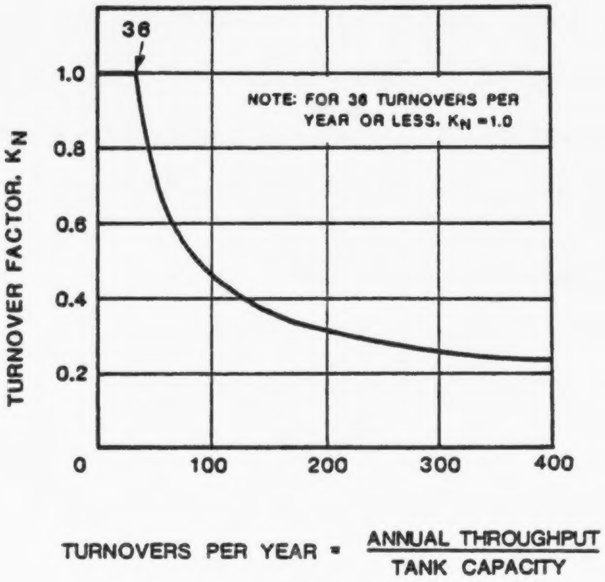


Figure 4.3-11. Turnover factor (K_N) for fixed roof tanks.

The fixed roof working loss (L_W) is the sum of the loading and unloading loss. API reports that special tank operating conditions may result in actual losses which are significantly greater or lower than the estimates provided by Equation (2).

The API recommends the use of these storage loss equations only for cases in which the stored petroleum liquids exhibit vapor pressures in the same range as gasolines. However, in the absence of any correlation developed specifically for naphthas, kerosenes, and fuel oils, it is recommended that these storage loss equations also be used for the storage of these heavier fuels.

The method most commonly used to control emissions from fixed roof tanks is a vapor recovery system that collects emissions from the storage vessels and converts them to liquid product. To recover vapor, one or a combination of four methods may be used: vapor/liquid absorption, vapor compression, vapor cooling, and vapor/solid adsorption. Overall control efficiencies of vapor recovery systems vary from 90 to 95 percent, depending on the method used, the design of the unit, the composition of vapors recovered, and the mechanical condition of the system.

Emissions from fixed roof tanks can also be controlled by the addition of an internal floating cover or covered floating roof to the existing fixed roof tank. API reports that this can result in an average loss reduction of 90 percent of the total evaporation loss sustained from a fixed roof tank.[8]

Evaporative emissions can be minimized by reducing tank heat input with water sprays, mechanical cooling, underground storage, tank insulation, and optimum scheduling of tank turnovers.

4.3.2.2 Floating Roof Tanks[3,7] - Floating roof standing storage losses can be estimated from:

$$L_S = 9.21 \times 10^{-3} M \left[\frac{P}{14.7 - P}\right]^{0.7} D^{1.5} V_w^{0.7} K_t K_s K_p K_c \qquad (3)$$

where: L_S = Floating roof standing storage loss (lb/day).

M = Molecular weight of vapor in storage tank (lb/lb mole); see Table 4.3-1.

P = True vapor pressure at bulk liquid conditions (psia); see Figures 4.3-8, 4.3-9, or Table 4.3-1.

D = Tank diameter (ft); see note (1).

V_w = Average wind velocity (mi/hr); see note (2).

K_t = Tank type factor (dimensionless); see Table 4.3-3.

K_s = Seal factor (dimensionless); see Table 4.3-3.

K_p = Paint factor (dimensionless); see Table 4.3-3.

K_c = Crude oil factor (dimensionless); see note (3).

Note: (1) For $D \geq 150$, use $D\sqrt{150}$ instead of $D^{1.5}$

(2) API correlation was derived for minimum wind velocity of 4 mph. If $V_w \leq 4$ mph, use $V_w = 4$mph.

(3) $K_c = (0.84)$ for crude oil, $K_c = (1.0)$ for all other liquids.

API reports that standing storage losses from gasoline and crude oil storage calculated from Equation (3) will not deviate from the actual losses by more than ±25 percent for tanks in good condition under normal operation. However, losses may exceed the calculated amount if the seals are in poor condition. Although the API recommends the use of these correlations only for petroleum liquids exhibiting vapor pressures in the range of gasoline and crude oils, in the absence of better correlations, these correlations are also recommended with caution for use with heavier naphthas, kerosenes, and fuel oils.

Table 4.3-3. TANK, TYPE, SEAL, AND PAINT FACTORS FOR FLOATING ROOF TANKS[2]

Tank type	K_t	Seal type	K_s
Welded tank with pan or pontoon roof, single or double seal	0.045	Tight fitting (typical of modern metallic and non-metallic seals)	1.00
Riveted tank with pontoon roof, double seal	0.11	Loose fitting (typical of seals built prior to 1942)	1.33
Riveted tank with pontoon roof, single seal	0.13	Paint color of shell and roof	K_p
Riveted tank with pan roof, double seal	0.13	Light gray or aluminum	1.0
Riveted tank with pan roof, single seal	0.14	White	0.9

API has developed a correlation based on laboratory data for calculating floating roof withdrawal loss for gasoline storage.[5] Floating roof withdrawal loss for gasoline can be estimated from:

$$L_{WD} = \frac{22.4\ d\ C_F}{D} \qquad (4)$$

where: L_{WD} = **Floating roof gasoline withdrawal loss (lb/10³ gal throughput).**

d = **Density of stored liquid at bulk liquid conditions (lb/gal); see Table 4.3-1.**

C_F = **Tank construction factor (dimensionless); see note.**

D = **Tank diameter (ft).**

Note: C_F = **(0.02) for steel tanks,** C_F = **(1.0) for gunite-lined tanks.**

Because Equation (4) was derived from gasoline data, its applicability to other stored liquids is uncertain. No estimate of accuracy of Equation (4) has been given.

API has not presented any correlations that specifically pertain to internal floating covers or covered floating roofs. Currently, API recommends the use of Equations (3) and (4) with a wind speed of 4 mph for calculating the losses from internal floating covers and covered floating roofs.

Evaporative emissions from floating roof tanks can be minimized by reducing tank heat input.

4.3.2.3 Variable Vapor Space Systems[4,7]- Variable vapor space system filling losses can be estimated from:

$$L_V = (2.40 \times 10^{-2})\ \frac{M\,P}{V_1}\left[(V_1) - (0.25\ V_2\ N)\right] \qquad (5)$$

where: L_V = Variable vapor space filling loss (lb/10^3 gal throughput).

M = Molecular weight of vapor in storage tank (lb/lb mole); see Table 4.3-1.

P = True vapor pressure at bulk liquid conditions (psia); see Figures 4.3-8, 4.3-9, or Table 4.3-1.

V_1 = Volume of liquid pumped into system: throughput (bbl).

V_2 = Volume expansion capacity of system (bbl); see note (1).

N = Number of transfers into system (dimensionless); see note (2).

Note: (1) V is the volume expansion capacity of the variable vapor space achieved by roof-lifting or diaphragm-flexing.

(2) N is the number of transfers into the system during the time period that corresponds to a throughput of V_1.

The accuracy of Equation (5) is not documented; however, API reports that special tank operating conditions may result in actual losses which are significantly different from the estimates provided by Equation (5). It should also be noted that, although not developed for use with heavier petroleum liquids such as kerosenes and fuel oils, Equation (5) is recommended for use with heavier petroleum liquids in the absence of better data.

Evaporative emissions from variable vapor space tanks are negligible and can be minimized by optimum scheduling of tank turnovers and by reducing tank heat input. Vapor recovery systems can be used with variable vapor space systems to collect and recover filling losses.

Vapor recovery systems capture hydrocarbon vapors displaced during filling operations and recover the hydrocarbon vapors by the use of refrigeration, absorption, adsorption, and/or compression. Control efficiencies range from 90 to 98 percent, depending on the nature of the vapors and the recovery equipment used.

4.3.2.4 Pressure Tanks - Pressure tanks incur vapor losses when excessive internal pressures result in relief valve venting. In some pressure tanks vapor venting is a design characteristic, and the vented vapors must be routed to a vapor recovery system. However, for most pressure tanks vapor venting is not a normal occurrence, and the tanks can be considered closed systems. Fugitive losses are also associated with pressure tanks and their equipment, but with proper system maintenance they are insignificant. Correlations do not exist for estimating vapor losses from pressure tanks.

4.3.3 Emission Factors

Equations (1) through (5) can be used to estimate evaporative losses, provided the respective parameters are known. For those cases where such parameters are unknown, Table 4.3-4 provides emission factors for the typical systems and conditions. It should be emphasized that these emission factors are rough estimates at best for storage of liquids other than gasoline and crude oil, and for storage conditions other than the ones they are based upon. In areas where storage sources contribute a substantial portion of the total evaporative emissions or where they are major factors affecting the air quality, it is advisable to obtain the necessary parameters and to calculate emission estimates using Equations (1) through (5).

Table 4.3-4. EVAPORATIVE EMISSION FACTORS FOR STORAGE TANKS WITHOUT CONTROLS[2-4,6,7]

Product Stored	Fixed roof tanks						Floating roof tanks						Variable vapor space tanks	
	Breathing loss						Standing storage loss						10,500 bbl	
	"New tank" conditions		"Old tank" conditions		Working loss		"New tank" conditions		"Old tank" conditions		Withdrawal loss		Filling loss	
	lb/day-10³ gal	kg/day-10³ liters	lb/day-10³ gal	kg/day-10³ liters	lb/10³ gal throughput	kg/10³ liters throughput	lb/day-10³ gal	kg/day-10³ liters	lb/day-10³ gal	kg/day-10³ liters	lb/10³ gal throughput	kg/10³ liters throughput	lb/10³ gal throughput	kg/10³ liters throughput
Fuels - 67,000 bbl tanks														
1. Gasoline RVP 13	0.30	0.036	0.34	0.041	10.0	1.2	0.044	0.0052	0.10	0.012	0.023	0.0028	9.6	1.2
2. Gasoline RVP 10	0.23	0.028	0.26	0.031	8.2	0.99	0.033	0.0040	0.078	0.0094	0.023	0.0028	7.7	0.93
3. Gasoline RVP 7	0.16	0.019	0.18	0.022	5.7	0.68	0.023	0.0028	0.055	0.0066	0.023	0.0028	5.4	0.65
4. Crude oil RVP 5	0.064	0.0077	0.073	0.0088	2.8	0.34	0.012	0.0014	0.028	0.0034			Not used	Not used
5. Jet naphtha (JP-4)	0.086	0.010	0.098	0.011	2.5	0.30	0.012	0.0014	0.028	0.0034			2.3	0.28
6. Jet kerosene	0.0043	0.00052	0.0049	0.00059	0.027	0.0032	0.00054	0.000065	0.0013	0.00016			0.025	0.0030
7. Distillate fuel no. 2	0.0039	0.00047	0.0044	0.00053	0.023	0.0028	0.00049	0.000058	0.0011	0.00014			0.022	0.0026
8. Residual oil no. 6	0.00016	0.000019	0.00018	0.000022	0.00018	0.000022	0.000018	0.0000022	0.000043	0.0000052			0.00017	0.000020
Fuels - 250,000 bbl tanks														
9. Gasoline RVP 13	0.22	0.026	0.25	0.030	10.0	1.2	0.025	0.0030	0.057	0.0068	0.013	0.0015	Not used	Not used
10. Gasoline RVP 10	0.17	0.020	0.19	0.023	8.2	0.99	0.019	0.0023	0.044	0.0053	0.013	0.0015	Not used	Not used
11. Gasoline RVP 7	0.12	0.014	0.13	0.016	5.7	0.68	0.013	0.0016	0.031	0.0037	0.013	0.0015	Not used	Not used
12. Crude oil RVP 5	0.046	0.0055	0.052	0.0062	2.8	0.34	0.0077	0.0092	0.018	0.0022			Not used	Not used
13. Jet naphtha (JP-4)	0.062	0.0074	0.071	0.0085	2.5	0.30	0.0068	0.00082	0.016	0.0019			Not used	Not used
14. Jet kerosene	0.0031	0.00037	0.0035	0.00042	0.027	0.0032	0.00031	0.000037	0.00074	0.000089			Not used	Not used
15. Distillate fuel no. 2	0.0028	0.00034	0.0032	0.00038	0.023	0.0028	0.00028	0.000034	0.00068	0.000082			Not used	Not used
16. Residual fuel no. 6	0.000012	0.0000014	0.000014	0.0000017	0.00018	0.000022	0.0000010	0.00000012	0.0000024	0.00000029			Not used	Not used
Petrochemicals* - 67,000 bbl tanks														
17. Acetone	0.12	0.014	0.14	0.016	4.0	0.48	0.017	0.0020	0.039	0.0047			3.8	0.45
18. Acrylonitrile	0.060	0.0072	0.068	0.0082	1.8	0.21	0.0084	0.0010	0.020	0.0024			1.7	0.20
19. Benzene	0.079	0.0094	0.090	0.011	2.2	0.27	0.011	0.0013	0.026	0.0031			2.1	0.25
20. Carbon disulfide	0.24	0.029	0.28	0.033	8.8	1.1	0.035	0.0042	0.083	0.0099			8.2	0.98
21. Carbon tetrachloride	0.17	0.021	0.20	0.024	5.2	0.62	0.024	0.0029	0.056	0.0069			4.8	0.58
22. Chloroform	0.21	0.025	0.24	0.029	7.1	0.86	0.030	0.0036	0.071	0.0085			6.7	0.80
23. Cyclohexane	0.085	0.010	0.096	0.012	2.4	0.29	0.012	0.0014	0.028	0.0034			2.3	0.27
24. 1,2-Dichloroethane	0.087	0.010	0.10	0.012	2.4	0.28	0.012	0.0014	0.029	0.0034			2.2	0.27
25. Ethyl acetate	0.083	0.010	0.095	0.011	2.3	0.28	0.012	0.0014	0.027	0.0033			2.2	0.26
26. Ethyl alcohol	0.028	0.0034	0.032	0.0038	0.66	0.079	0.0039	0.00046	0.0091	0.0011			0.62	0.074
27. Isopropyl alcohol	0.031	0.0038	0.036	0.0043	0.72	0.086	0.0043	0.00052	0.010	0.0012			0.68	0.082
28. Methyl alcohol	0.036	0.0044	0.042	0.0050	1.1	0.13	0.0051	0.00061	0.012	0.0014			1.0	0.12
29. Methylene chloride	0.31	0.037	0.35	0.042	11.0	1.3	0.044	0.0053	0.10	0.012			10.0	1.2
30. Methyl-ethyl-ketone	0.073	0.0087	0.083	0.0099	2.1	0.25	0.010	0.0012	0.024	0.0029			1.9	0.23
31. Methyl methacrylate	0.038	0.0046	0.043	0.0052	0.72	0.086	0.0051	0.00061	0.012	0.0015			0.68	0.082
32. 1,1,1-Trichloroethane	0.17	0.020	0.19	0.023	5.1	0.61	0.023	0.0028	0.055	0.0066			4.8	0.58
33. Trichloroethylene	0.11	0.013	0.12	0.014	2.8	0.34	0.015	0.0018	0.035	0.0042			2.6	0.31
34. Toluene	0.035	0.0042	0.040	0.0048	0.66	0.079	0.0048	0.00058	0.011	0.0014			0.62	0.074
35. Vinyl acetate	0.092	0.011	0.10	0.013	2.7	0.32	0.013	0.0016	0.030	0.0037			2.5	0.30

*Due to safety and health regulations, toxicity, and value of these petrochemicals, they are normally stored in tanks with vapor recovery controls which are 90 to 98 percent efficient.

Emission factors based on the following parameters:

Ambient conditions:
Storage temperature: 60°F (15.6°C)
Daily ambient temperature change: 15°F (8.3°C)
Wind velocity: 10 mi/hr (4.5 m/sec)

Typical fixed roof tanks:
Outage: 50 percent of tank height
Turnovers per year (N): 30 for crude; 13 for all other liquids
Paint factor (F_p): New tank-white paint-1.00
Old tank-white aluminum paint-1.14

For 67,000 bbl tankage (10.7×10^6 liters):
Height: 48 ft (14.6m)
Diameter: 110 ft (33.5m)

For 250,000 bbl tankage (39.7×10^6 liters):
Height: 44 ft (13.4m)
Diameter: 200 ft (60.8m)

Emission factors based on the following parameters:

Typical floating roof tanks:
Paint factor (K_p): New tank-white paint-0.90
Old tank-white aluminum paint-0.95
Seal factor (K_s): New tank-modern seals-1.00
Old tank-50 percent old seals-1.14
Tank type factor (K_t): New tank-welded-0.045
Old tank-50 percent riveted-0.088

Typical variable vapor space tank:
Diameter: 50 ft (15.2m)
Height: 30 ft (9.1m)
Capacity: 10,500 bbl (1.67×10^6 liters)
Turnovers per year (N): 6
Volume expansion capacity: one fourth of liquid capacity (2625 bbl (0.42×10^6 liters))

4.3.3.1 **Sample Calculation** - Breathing losses from a fixed roof storage tank would be calculated as follows, using Equation (1).

Design basis:

Tank capacity - 100,000 bbl.
Tank diameter - 125 ft.
Tank height - 46 ft.
Average diurnal temperature change - 15°F.
Gasoline RVP - 9 psia.
Gasoline temperature - 70°F.
Specular aluminum painted tank.
Roof slope is 0.1 ft/ft.

Fixed roof tank breathing loss equation:

$$L_B = 2.21 \times 10^{-4} M \left[\frac{P}{14.7 - P}\right]^{0.68} D^{1.73}\ H^{0.51}\ \Delta T^{0.50}\ F_p\ C\ K_c$$

where: M = Molecular weight of gasoline vapors (see Table 4.3-1)= 66.

P = True vapor of gasoline (see Figure 4.3-8) = 5.6 psia.

D = Tank diameter = 125 ft.

ΔT = average diurnal temperature change = 15°F.

F_p = paint factor (see Table 4.3-2) = 1.20.

C = tank diameter adjustment factor (see Figure 4.3-10) = 1.0.

K_c = crude oil factor (see note for equation (1)) = 1.0.

H = average vapor space height. For a tank which is filled completely and emptied, the average liquid level is 1/2 the tank rim height, or 23 ft. The effective cone height is 1/3 of the cone height. The roof slope is 0.1 ft/ft and the tank radius is 62.5 ft. Effective cone height = (62.5 ft) (0.1 ft/ft) (1/3) = 2.08 ft.

H = average vapor space height = 23 ft + 2 ft = 25 ft.

Therefore:

$$L_B = 2.21 \times 10^{-4}\,(66) \left[\frac{5.6}{14.7 - 5.6}\right]^{0.68} (125)^{1.73}\ (25)^{0.51}\ (15)^{0.50}\ (1.2)(1.0)(1.0)$$

$$L_B = 1068 \text{ lb/day}$$

References for Section 4.3

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2. American Petroleum Inst., Evaporation Loss Committee. Evaporation Loss From Fixed-Roof Tanks. Bull. 2518. Washington, D.C. 1962.

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9. Barnett, Henry C. et al. Properties Of Aircraft Fuels. Lewis Flight Propulsion Lab., Cleveland, Ohio. NACA-TN 3276. August 1956.

4.4 TRANSPORTATION AND MARKETING OF PETROLEUM LIQUIDS[1]

by Charles C. Masser

4.4.1 Process Description

As Figure 4.4-1 indicates, the transportation and marketing of petroleum liquids involves many distinct operations, each of which represents a potential source of hydrocarbon evaporation loss. Crude oil is transported from production operations to the refinery via tankers, barges, tank cars, tank trucks, and pipelines. In the same manner, refined petroleum products are conveyed to fuel marketing terminals and petrochemical industries by tankers, barges, tank cars, tank trucks, and pipelines. From the fuel marketing terminals, the fuels are delivered via tank trucks to service stations, commercial accounts, and local bulk storage plants. The final destination for gasoline is usually a motor vehicle gasoline tank. A similar distribution path may also be developed for fuel oils and other petroleum products.

4.4.2 Emissions and Controls

Evaporative hydrocarbon emissions from the transportation and marketing of petroleum liquids may be separated into four categories, depending on the storage equipment and mode of transportation used:

1. Large storage tanks: Breathing, working, and standing storage losses.
2. Marine vessels, tank cars, and tank trucks: Loading, transit, and ballasting losses.
3. Service stations: Bulk fuel drop losses and underground tank breathing losses.
4. Motor vehicle tanks: Refueling losses.

(In addition, evaporative and exhaust emissions are also associated with motor vehicle operation. These topics are discussed in Chapter 3.)

4.4.2.1 Large Storage Tanks - Losses from storage tanks are thoroughly discussed in Section 4.3.

4.4.2.2 Marine Vessels, Tank Cars, and Tank Trucks - Losses from marine vessels, tank cars, and tank trucks can be categorized into loading losses, transit losses, and ballasting losses.

Loading losses are the primary source of evaporative hydrocarbon emissions from marine vessel, tank car, and tank truck operations. Loading losses occur as hydrocarbon vapors residing in empty cargo tanks are displaced to the atmosphere by the liquid being loaded into the cargo tanks. The hydrocarbon vapors displaced from the cargo tanks are a composite of (1) hydrocarbon vapors formed in the empty tank by evaporation of residual product from previous hauls and (2) hydrocarbon vapors generated in the tank as the new product is being loaded. The quantity of hydrocarbon losses from loading operations is, therefore, a function of the following parameters:

- Physical and chemical characteristics of the previous cargo.
- Method of unloading the previous cargo.

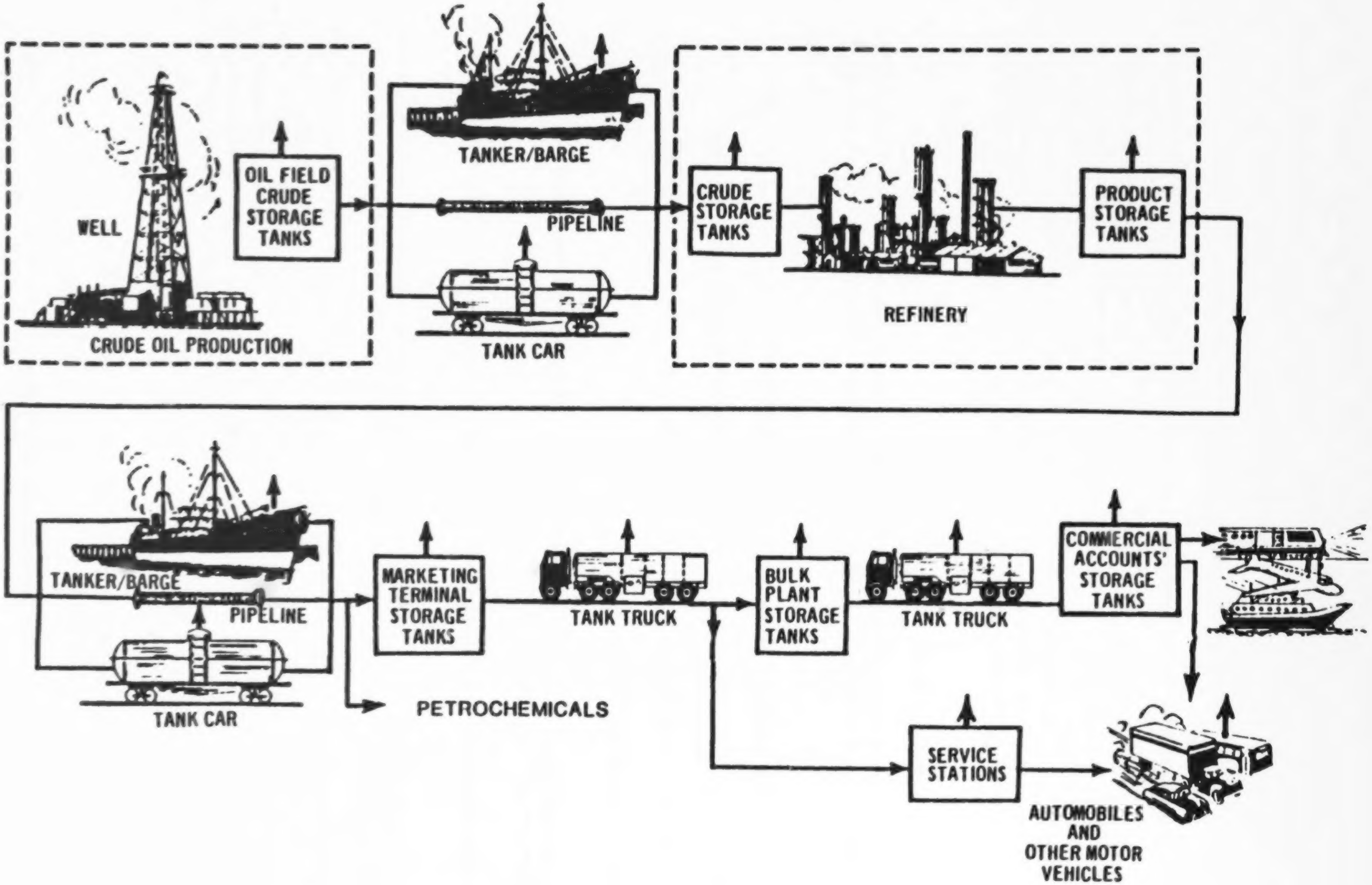
WELL
OIL FIELD CRUDE STORAGE TANKS
CRUDE OIL PRODUCTION
TANKER/BARGE
PIPELINE
TANK CAR
CRUDE STORAGE TANKS
REFINERY
PRODUCT STORAGE TANKS
TANKER/BARGE
PIPELINE
TANK CAR
MARKETING TERMINAL STORAGE TANKS
PETROCHEMICALS
TANK TRUCK
BULK PLANT STORAGE TANKS
TANK TRUCK
COMMERCIAL ACCOUNTS' STORAGE TANKS
SERVICE STATIONS
AUTOMOBILES AND OTHER MOTOR VEHICLES

Figure 4.4-1. Flowsheet of petroleum production, refining, and distribution systems. (Sources of organic evaporative emissions are indicated by vertical arrows.)

- Operations during the transport of the empty carrier to the loading terminal.
- Method of loading the new cargo.
- Physical and chemical characteristics of the new cargo.

The principal methods of loading cargo carriers are presented in Figures 4.4-2, 4.4-3, and 4.4-4. In the splash loading method, the fill pipe dispensing the cargo is only partially lowered into the cargo tank. Significant turbulence and vapor-liquid contacting occurs during the splash loading operation, resulting in high levels of vapor generation and loss. If the turbulence is high enough, liquid droplets will be entrained in the vented vapors.

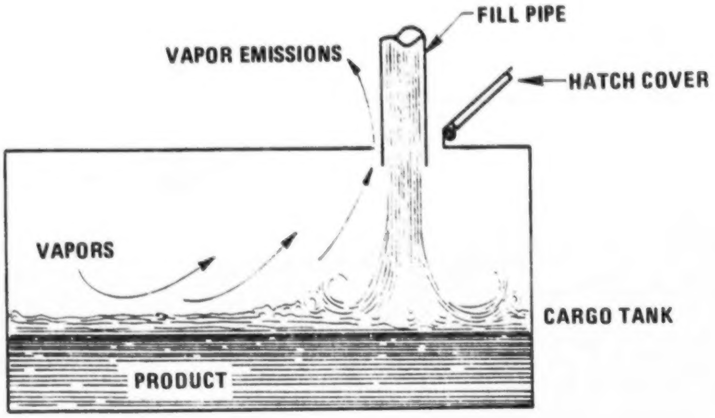
FILL PIPE
VAPOR EMISSIONS
HATCH COVER
VAPORS
CARGO TANK
PRODUCT

Figure 4.4-2. Splash loading method.

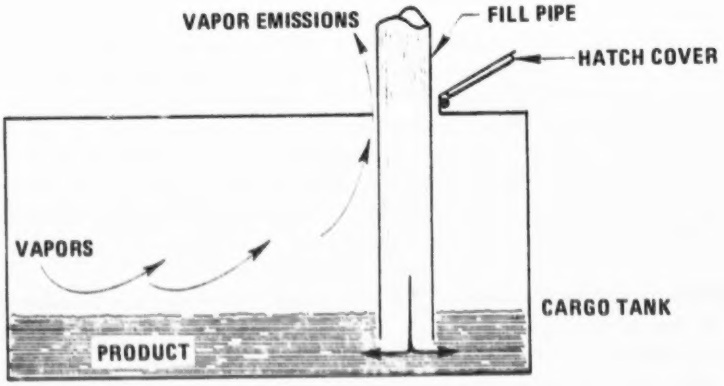
VAPOR EMISSIONS
FILL PIPE
HATCH COVER
VAPORS
CARGO TANK
PRODUCT

Figure 4.4-3. Submerged fill pipe.

A second method of loading is submerged loading. The two types of submerged loading are the submerged fill pipe method and the bottom loading method. In the submerged fill pipe method, the fill pipe descends almost to the bottom of the cargo tank. In the bottom loading method, the fill pipe enters the cargo tank from the bottom. During the major portion of both forms of submerged loading

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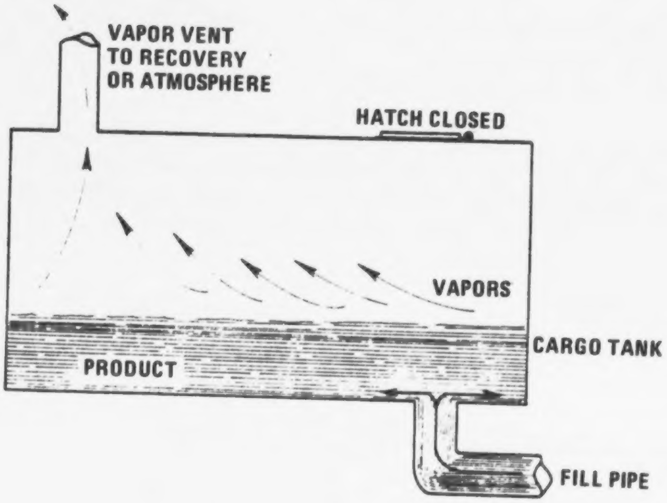


Figure 4.4-4. Bottom loading.

methods, the fill pipe opening is positioned below the liquid level. The submerged loading method significantly reduces liquid turbulence and vapor-liquid contacting, thereby resulting in much lower hydrocarbon losses than encountered during splash loading methods.

The history of a cargo carrier is just as important a factor in loading losses as the method of loading. Hydrocarbon emissions are generally lowest from a clean cargo carrier whose cargo tanks are free from vapors prior to loading. Clean cargo tanks normally result from either carrying a non-volatile liquid such as heavy fuel oils in the previous haul, or from cleaning or venting the empty cargo tank prior to loading operations. An additional practice, specific to marine vessels, that has significant impact on loading losses is ballasting. After unloading a cargo, empty tankers normally fill several cargo tanks with water to improve the tanker's stability on the return voyage. Upon arrival in port, this ballast water is pumped from the cargo tanks before loading the new cargo. The ballasting of cargo tanks reduces the quantity of vapor returning in the empty tanker, thereby reducing the quantity of vapors emitted during subsequent tanker loading operations.

In normal dedicated service, a cargo carrier is dedicated to the transport of only one product and does not clean or vent its tank between trips. An empty cargo tank in normal dedicated service will retain a low but significant concentration of vapors which were generated by evaporation of residual product on the tank surfaces. These residual vapors are expelled along with newly generated vapors during the subsequent loading operation.

Another type of cargo carrier is one in "dedicated balance service." Cargo carriers in dedicated balance service pick up vapors displaced during unloading operations and transport these vapors in the empty cargo tanks back to the loading terminal. Figure 4.4-5 shows a tank truck in dedicated vapor balance service unloading gasoline to an underground service station tank and filling up with displaced gasoline vapors to be returned to the truck loading terminal. The vapors in an empty cargo carrier in dedicated balance service are normally saturated with hydrocarbons.

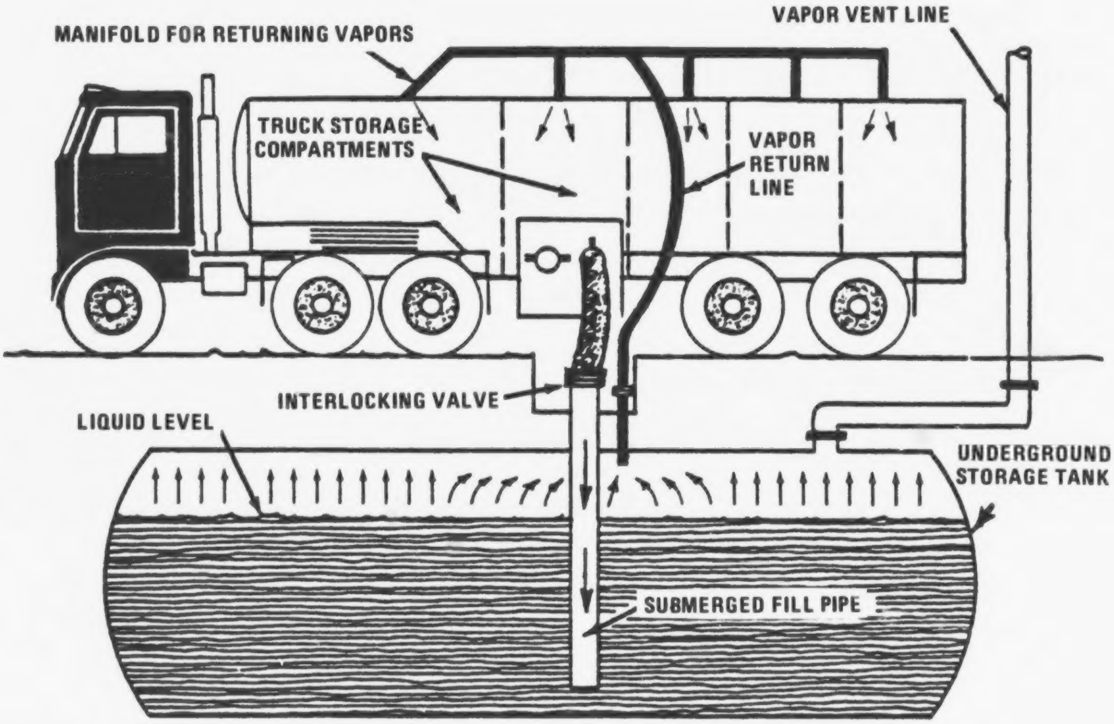

MANIFOLD FOR RETURNING VAPORS
VAPOR VENT LINE
TRUCK STORAGE COMPARTMENTS
VAPOR RETURN LINE
INTERLOCKING VALVE
LIQUID LEVEL
UNDERGROUND STORAGE TANK
SUBMERGED FILL PIPE

Figure 4.4-5. Tanktruck unloading into an underground service station storage tank. Tanktruck is practicing "vapor balance" form of vapor control.

Emissions from loading hydrocarbon liquid can be estimated (within 30 percent) using the following expression:

$$L_L = 12.46 \frac{SPM}{T} \qquad (1)$$

where: L_L = **Loading loss, lb/10^3 gal of liquid loaded.**

M = **Molecular weight of vapors, lb/lb-mole (see Table 4.3-1).**

P = **True vapor pressure of liquid loading, psia (see Figures 4.3-8 and 4.3-9, and Table 4.3-1).**

T = **Bulk temperature of liquid loaded, °R.**

S = **A saturation factor (see Table 4.4-1).**

The saturation factor (S) represents the expelled vapor's fractional approach to saturation and accounts for the variations observed in emission rates from the different unloading and loading methods. Table 4.4-1 lists suggested saturation factors (S).

Table 4.4-1. S FACTORS FOR CALCULATING PETROLEUM LOADING LOSSES

Cargo carrier	Mode of operation	S factor
Tank trucks and tank cars	Submerged loading of a clean cargo tank	0.50
	Splash loading of a clean cargo tank	1.45
	Submerged loading: normal dedicated service	0.60
	Splash loading: normal dedicated service	1.45
	Submerged loading: dedicated, vapor balance service	1.00
	Splash loading: dedicated, vapor balance service	1.00
Marine vessels[a]	Submerged loading: ships	0.2
	Submerged loading: barges	0.5

[a] To be used for products other than gasoline; use factors from Table 4.4-2 for marine loading of gasoline.

Recent studies on gasoline loading losses from ships and barges have led to the development of more accurate emission factors for these specific loading operations. These factors are presented in Table 4.4-2 and should be used instead of Equation (1) for gasoline loading operations at marine terminals.[2]

Ballasting operations are a major source of hydrocarbon emissions associated with unloading petroleum liquids at marine terminals. It is common practice for large tankers to fill several cargo tanks with water after unloading their cargo. This water, termed ballast, improves the stability of the empty tanker on rough seas during the subsequent return voyage. Ballasting emissions occur as hydrocarbon-laden air in the empty cargo tank is displaced to the atmosphere by ballast water being pumped into the empty cargo tank. Although ballasting practices vary quite a bit, individual cargo tanks are ballasted about 80 percent, and the total vessel is ballasted approximately 40 percent of capacity. Ballasting emissions from gasoline and crude oil tankers are approximately 0.8 and 0.6 lb/10^3 gal, respectively, based on total tanker capacity. These estimates are for motor gasolines and medium volatility crudes (RVP$\approx$5 psia).[2]

An additional emission source associated with marine vessel, tank car, and tank truck operations is transit losses. During the transportation of petroleum liquids, small quantities of hydrocarbon vapors are expelled from cargo tanks due to temperature and barometric pressure changes. The most significant transit loss is from tanker and barge operations and can be calculated using Equation (2).[3]

Table 4.4-2. HYDROCARBON EMISSION FACTORS FOR GASOLINE LOADING OPERATIONS

	Hydrocarbon emission factors					
	Ships		Ocean barges		Barges	
Vessel tank condition	Range	Average	Range	Average	Range	Average
Cleaned and vapor free						
lb/10^3 gal transferred	0 to 2.3	1.0	0 to 3	1.3	a	1.2
kg/10^3 liter transferred	0 to 0.28	0.12	0 to 0.36	0.16		0.14
Ballasted						
lb/10^3 gal transferred	0.4 to 3	1.6	0.5 to 3	2.1	b	b
kg/10^3 liter transferred	0.05 to 0.36	0.19	0.06 to 0.36	0.25		
Uncleaned - dedicated service						
lb/10^3 gal transferred	0.4 to 4	2.4	0.5 to 5	3.3	1.4 to 9	4.0
kg/10^3 liter transferred	0.05 to 0.48	0.29	0.06 to 0.60	0.40	0.17 to 1.08	0.48
Average cargo tank condition						
lb/10^3 gal transferred	a	1.4	a	a	a	4.0
kg/10^3 liter transferred		0.17				0.48

[a] These values are not available.

[b] Barges are not normally ballasted.

$$L_T = 0.1\ PW \qquad (2)$$

where: L_T = Transit loss, lb/week-10^3 gal transported.

P = True vapor pressure of the transported liquid, psia (see Figures 4.3-8 and 4.3-9, and Table 4.3-1).

W = Density of the condensed vapors, lb/gal (see Table 4.3-1).

In the absence of specific inputs for Equations (1) and (2), typical evaporative hydrocarbon emissions from loading operations are presented in Table 4.4-3. It should be noted that, although the crude oil used to calculate the emission values presented in Table 4.4-3 has an RVP of 5, the RVP of crude oils can range over two orders of magnitude. In areas where loading and transportation sources are major factors affecting the air quality it is advisable to obtain the necessary parameters and to calculate emission estimates from Equations (1) and (2).

Control measures for reducing loading emissions include the application of alternate loading methods producing lower emissions and the application of vapor recovery equipment. Vapor recovery equipment captures hydrocarbon vapors displaced during loading and ballasting operations and recovers the hydrocarbon vapors by the use of refrigeration, absorption, adsorption, and/or compression. Figure 4.4-6 demonstrates the recovery of gasoline vapors from tank trucks during loading operation at bulk terminals. Control efficiencies range from 90 to 98 percent depending on the nature of the vapors and the type of recovery equipment employed.[4]

Table 4.4-3. HYDROCARBON EMISSION FACTORS FOR PETROLEUM LIQUID TRANSPORTATION AND MARKETING SOURCES

Emission source	Product emission factors					
	Gasoline	Crude oil	Jet naphtha (JP-4)	Jet kerosene	Distillate oil No. 2	Residual oil No. 6
Tank cars/trucks						
Submerged loading-normal service						
$lb/10^3$ gal transferred	5	3	1.5	0.02	0.01	0.0001
$kg/10^3$ liters transferred	0.6	0.4	0.18	0.002	0.001	0.00001
Splash loading-normal service						
$lb/10^3$ gal transferred	12	7	4	0.04	0.03	0.0003
$kg/10^3$ liters transferred	1.4	0.8	0.5	0.005	0.004	0.00004
Submerged loading-balance service						
$lb/10^3$ gal transferred	8	5	2.5	a	a	a
$kg/10^3$ liters transferred	1.0	0.6	0.3			
Splash loading-balance service						
$lb/10^3$ gal transferred	8	5	2.5	a	a	a
$kg/10^3$ liters transferred	1.0	0.6	0.3			
Marine vessels						
Loading tankers						
$lb/10^3$ gal transferred	b	0.7	0.5	0.005	0.005	0.00004
$kg/10^3$ liters transferred		0.08	0.06	0.0006	0.0006	5×10^{-6}
Loading barges						
$lb/10^3$ gal transferred	b	1.7	1.2	0.013	0.012	0.00009
$kg/10^3$ liters transferred		0.20	0.14	0.0016	0.0014	1.1×10^{-5}
Tanker ballasting						
$lb/10^3$ gal cargo capacity	0.8	0.6	c	c	c	c
$kg/10^3$ liters cargo capacity	0.10	0.07				
Transit						
$lb/week\text{-}10^3$ gal transported	3	1	0.7	0.02	0.005	3×10^{-5}
$kg/week\text{-}10^3$ liters transported	0.4	0.1	0.08	0.002	0.0006	4×10^{-6}

1. Emission factors are calculated for dispensed fuel temperature of 60°F.
2. The example gasoline has an RVP of 10 psia.
3. The example crude oil has an RVP of 5 psia.

a. Not normally used.
b. See Table 4.4-2 for these emission factors.
c. Not Available.

Emissions from controlled loading operations can be calculated by multiplying the uncontrolled emission rate calculated in Equations (1) and (2) by the control efficiency term:

$$\left[1 - \frac{\text{efficiency}}{100}\right]$$

4.4.2.3 Sample Calculation - Loading losses from a gasoline tank truck in dedicated balance service and practicing vapor recovery would be calculated as follows using Equation (1).

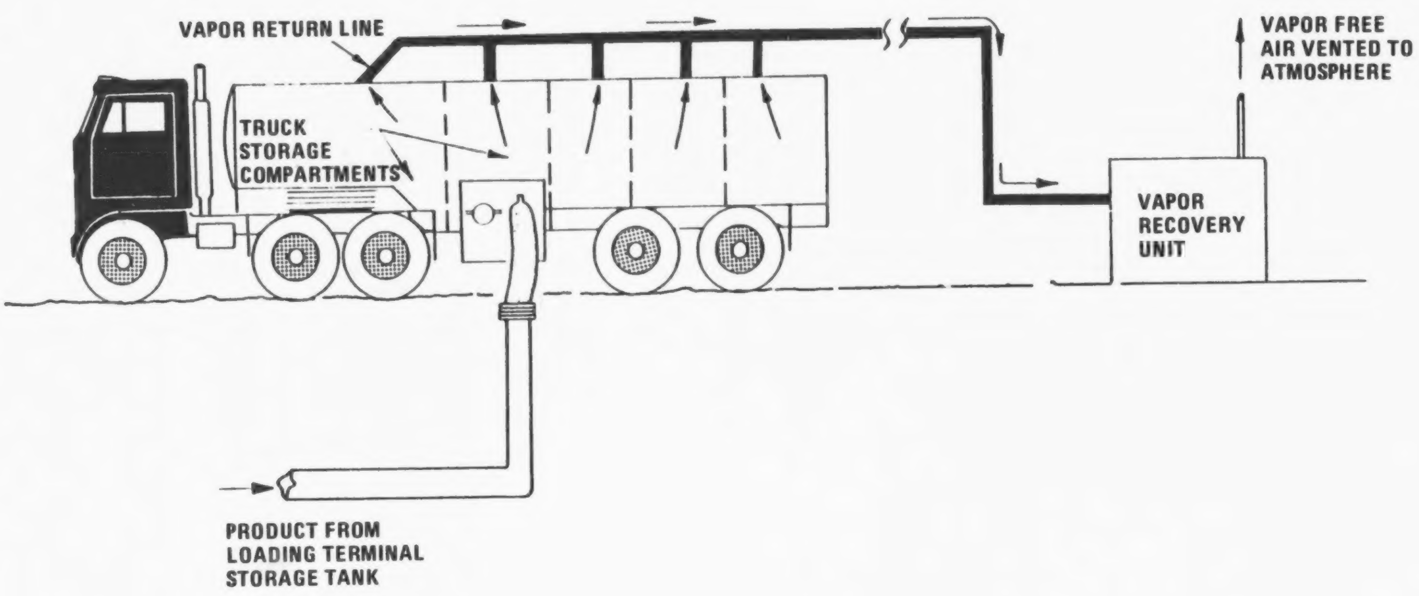

VAPOR RETURN LINE
TRUCK STORAGE COMPARTMENTS
VAPOR FREE AIR VENTED TO ATMOSPHERE
VAPOR RECOVERY UNIT
PRODUCT FROM LOADING TERMINAL STORAGE TANK

Figure 4.4-6. Tanktruck loading with vapor recovery.

Design basis:

Tank truck volume is 8000 gallons
Gasoline RVP is 9 psia
Dispensing temperature is 80°F
Vapor recovery efficiency is 95%

Loading loss equation:

$$L_L = 12.46 \frac{SPM}{T} \left(1 - \frac{eff}{100}\right)$$

where: S = Saturation factor (see Table 4.4-1) = 1.0
P = True vapor pressure of gasoline (see Figure 4.3-8) = 6.6 psia
M = Molecular weight of gasoline vapors (see Table 4.3-1) ≈66
T = Temperature of gasoline = 540°R
eff = The control efficiency = 95%

$$L_L = 12.46 \frac{(1.0)(6.6)(66)}{540} \left(1 - \frac{95}{100}\right)$$

$$= 0.50 \text{ lb}/10^3 \text{ gal}$$

Total loading losses are

$(0.50 \text{ lb}/10^3 \text{ gal})(8.0 \times 10^3 \text{ gal}) = 4.0$ lb of hydrocarbon

4.4.2.4 Service Stations - Another major source of evaporative hydrocarbon emissions is the filling of underground gasoline storage tanks at service stations. Normally, gasoline is delivered to service stations in large (8000 gallon) tank trucks. Emissions are generated when hydrocarbon vapors in the underground storage tank are displaced to the atmosphere by the gasoline being loaded into the tank. As with other loading losses, the quantity of the service station tank loading loss depends on several variables including the size and length of the fill pipe, the method of filling, the tank configuration, and the gasoline temperature, vapor pressure, and composition. An average hydrocarbon emission rate for submerged filling is 7.3 lb/10^3 gallons of transferred gasoline, and the rate for splash filling is 11.5 lb/10^3 gallons of transferred gasoline (Table 4.4-4).[4]

Emissions from underground tank filling operations at service stations can be reduced by the use of the vapor balance system (Figure 4.4-5). The vapor balance system employs a vapor return hose which returns gasoline vapors displaced from the underground tank to the tank truck storage compartments being emptied. The control efficiency of the balance system ranges from 93 to 100 percent. Hydrocarbon emissions from underground tank filling operations at a service station employing the vapor balance system and submerged filling are not expected to exceed 0.3 lb/10^3 gallons of transferred gasoline.

Table 4.4-4. HYDROCARBON EMISSIONS FROM GASOLINE SERVICE STATION OPERATIONS

Emission source	Emission rate	
	lb/10^3 gal throughput	kg/10^3 liters throughput
Filling underground tank		
Submerged filling	7.3	0.88
Splash filling	11.5	1.38
Balanced submerged filling	0.3	0.04
Underground tank breathing	1	0.12
Vehicle refueling operations		
Displacement losses (uncontrolled)	9	1.08
Displacement losses (controlled)	0.9	0.11
Spillage	0.7	0.084

A second source of hydrocarbon emissions from service stations is underground tank breathing. Breathing losses occur daily and are attributed to temperature changes, barometric pressure changes, and gasoline evaporation. The type of service station operation also has a large impact on breathing losses. An average breathing emission rate is 1 lb/10^3 gallons throughput.[5]

4.4.2.5 Motor Vehicle Refueling - An additional source of evaporative hydrocarbon emissions at service stations is vehicle refueling operations. Vehicle refueling emissions are attributable to vapors displaced from the automobile tank by dispensed gasoline and to spillage. The quantity of displaced vapors is dependent on gasoline temperature, auto tank temperature, gasoline RVP, and dispensing rates. Although several correlations have been developed to estimate losses due to displaced vapors, significant controversy exists concerning these correlations. It is estimated that the hydrocarbon emissions due to vapors displaced during vehicle refueling average 9 lb/10^3 gallons of dispensed gasoline.[4,5]

The quantity of spillage loss is a function of the type of service station, vehicle tank configuration, operator technique, and operation discomfort indices. An overall average spillage loss is 0.7 lb/10^3 gallons of dispensed gasoline.[6]

Control methods for vehicle refueling emissions are based on conveying the vapors displaced from the vehicle fuel tank to the underground storage tank vapor space through the use of a special hose and nozzle (Figure 4.4-7). In the "balance" vapor control system, the vapors are conveyed by natural pressure differentials established during refueling. In "vacuum assist" vapor control systems, the conveyance of vapors from the auto fuel tank to the underground fuel tank is assisted by a vacuum pump. The overall control efficiency of vapor control systems for vehicle refueling emissions is estimated to be 88 to 92 percent.[4]

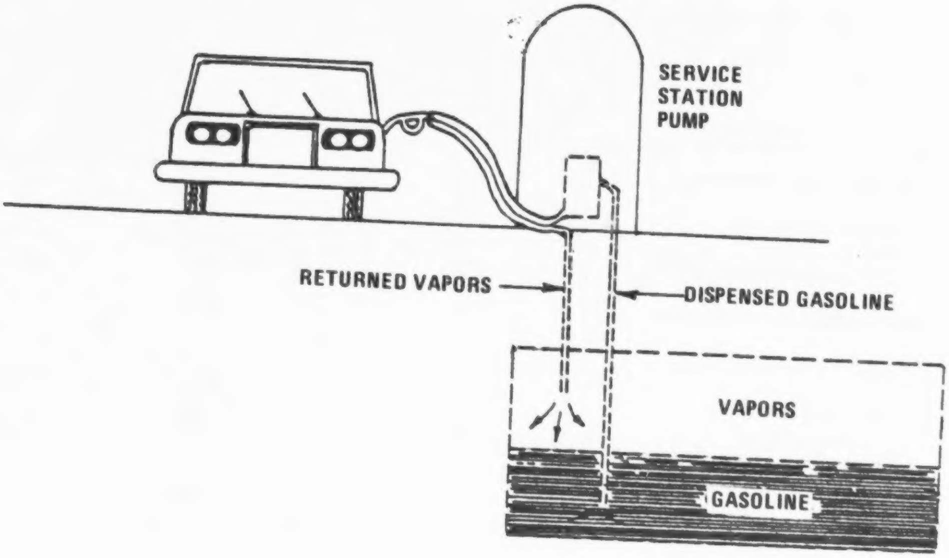


Figure 4.4-7. Automobile refueling vapor-recovery system.

References for Section 4.4

1. Burklin, C.E. and R.L. Honerkamp. Revision of Evaporative Hydrocarbon Emission Factors. Research Triangle Park, N.C. EPA Report No. 450/3-76-039. August 15, 1976.

2. Burklin, Clinton E. et al. Background Information on Hydrocarbon Emissions From Marine Terminal Operations, 2 Vols., EPA Report No. 450/3-76-038a and b. Research Triangle Park, N.C. November 1976.

3. American Petroleum Inst., Evaporation Loss Committee. Evaporation Loss From Tank Cars, Tank Trucks, and Marine Vessels. Washington, D.C. Bull. 2514. 1959.

4. Burklin, Clinton E. et al. Study of Vapor Control Methods For Gasoline Marketing Operations, 2 Vols. Radian Corporation. Austin, Texas. May 1975.

5. Scott Research Laboratories, Inc. Investigation Of Passenger Car Refueling Losses, Final Report, 2nd year program. EPA Report No. APTD-1453. Research Triangle Park, N.C. September 1972.

6. Scott Research Laboratories, Inc. Mathematical Expressions Relating Evaporative Emissions From Motor Vehicles To Gasoline Volatility, summary report. Plumsteadville, Pennsylvania. API Publication 4077. March 1971.

5. CHEMICAL PROCESS INDUSTRY

This section deals with emissions from the manufacture and use of chemicals or chemical products. Potential emissions from many of these processes are high, but because of the nature of the compounds they are usually recovered as an economic necessity. In other cases, the manufacturing operation is run as a closed system allowing little or no escape to the atmosphere.

In general, the emissions that reach the atmosphere from chemical processes are primarily gaseous and are controlled by incineration, adsorption, or absorption. In some cases, particulate emissions may also be a problem. The particulates emitted are generally extremely small and require very efficient treatment for removal. Emission data from chemical processes are sparse. It was therefore frequently necessary to make estimates of emission factors on the basis of material balances, yields, or similar processes.

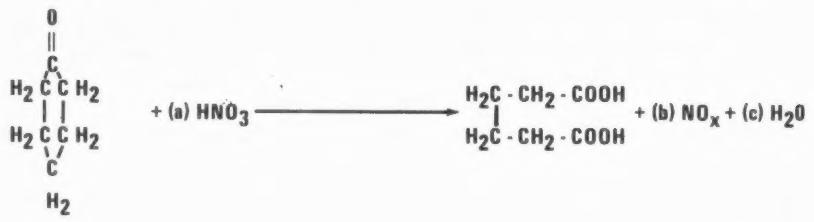
5.1 ADIPIC ACID

by Pam Canova

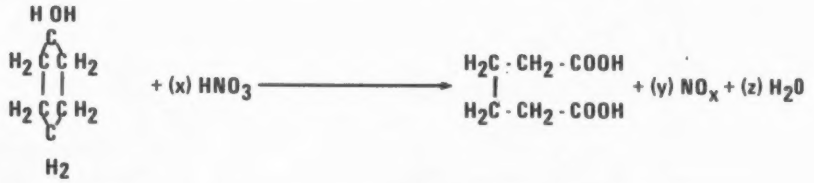
5.1.1 General[1,2]

Adipic acid, $HOOC(CH_2)_4COOH$, is a white crystalline solid used in the manufacture of synthetic fibers, coatings, plastics, urethane foams, elastomers, and synthetic lubricants. Ninety percent of all adipic acid produced in the United States is used in manufacturing Nylon 6,6. Cyclohexane is generally the basic raw material used to produce adipic acid; however, one plant uses cyclohexanone, which is a by-product of another process. Phenol has also been utilized, but has proved to be more expensive and less readily available than cyclohexane.

During adipic acid production, the raw material, cyclohexane or cyclohexanone, is transferred to a reactor, where it is oxidized at 260 to 330°F (130 to 170°C) to form a cyclohexanol/cyclohexanone mixture. The mixture is then transferred to a second reactor and oxidized with nitric acid and a catalyst (usually a mixture of cupric nitrate and ammonium vanadate) at 160 to 220°F (70 to 100°C) to form adipic acid. The chemistry of these reactions is shown below.



Cyclohexanone + Nitric acid → Adipic acid + Nitrogen oxides + Water



Cyclohexanol + Nitric acid → Adipic acid + Nitrogen oxides + Water

Dissolved NO_x gas plus any light hydrocarbon by-products are stripped from the adipic acid/nitric acid solution with air and steam. Various organic acid by-products, namely acetic acid, glutaric acid, and succinic acid, are also formed and may be recovered and sold by some plants.

The adipic acid/nitric acid solution is then chilled, and sent to a crystallizer where adipic acid crystals are formed. The solution is centrifuged to separate the crystals. The remaining solution is sent to another crystallizer, where any residual adipic acid is crystallized and centrifugally separated. The crystals from the two centrifuges are combined, dried, and stored. The remaining solution is distilled to recover nitric acid, which is routed back to the second reactor for re-use. Figure 5.1-1 presents a general schematic of the adipic acid manufacturing process.

5.1.2 Emissions and Controls

Nitrogen oxides, hydrocarbons, and carbon monoxide are the major pollutants produced in adipic acid production. The cyclohexane reactor is the largest source of CO and HC, and the nitric acid reactor is the predominant source of NO_x. Particulate emissions are low because baghouses are generally employed for maximum product recovery and air pollution control. Figure 5.1-1 shows the points of emission of these pollutants.

The most significant emissions of HC and CO come from the cyclohexane oxidation unit, which is equipped with high- and low-pressure scrubbers. Scrubbers have a 90 percent collection efficiency of HC and are used for economic reasons to recover expensive hydrocarbons as well as for pollution control. Thermal incinerators, flaring, and carbon absorbers can all be used to limit HC emissions from the cyclohexane oxidation unit with greater than 90 percent efficiency. CO boilers control CO emissions with 99.99 percent efficiency and HC emissions with practically 100 percent efficiency. The combined use of a CO boiler and a pressure scrubber results in essentially complete HC and CO control.

Three methods are presently used to control emissions from the NO_x absorber: water scrubbing, thermal reduction, and flaring or combustion in a powerhouse boiler. Water scrubbers have a low collection efficiency of approximately 70 percent because of the extended length of time needed to remove insoluble NO in the absorber offgas stream. Thermal reduction, in which offgases containing NO_x are heated to high temperatures and reacted with excess fuel in a reducing atmosphere, operates at up to 97.5 percent efficiency and is believed to be the most effective system of control. Burning offgas in a powerhouse or flaring has an estimated efficiency of 70 percent.

Emission factors for adipic acid manufacture are listed in Table 5.1-1.

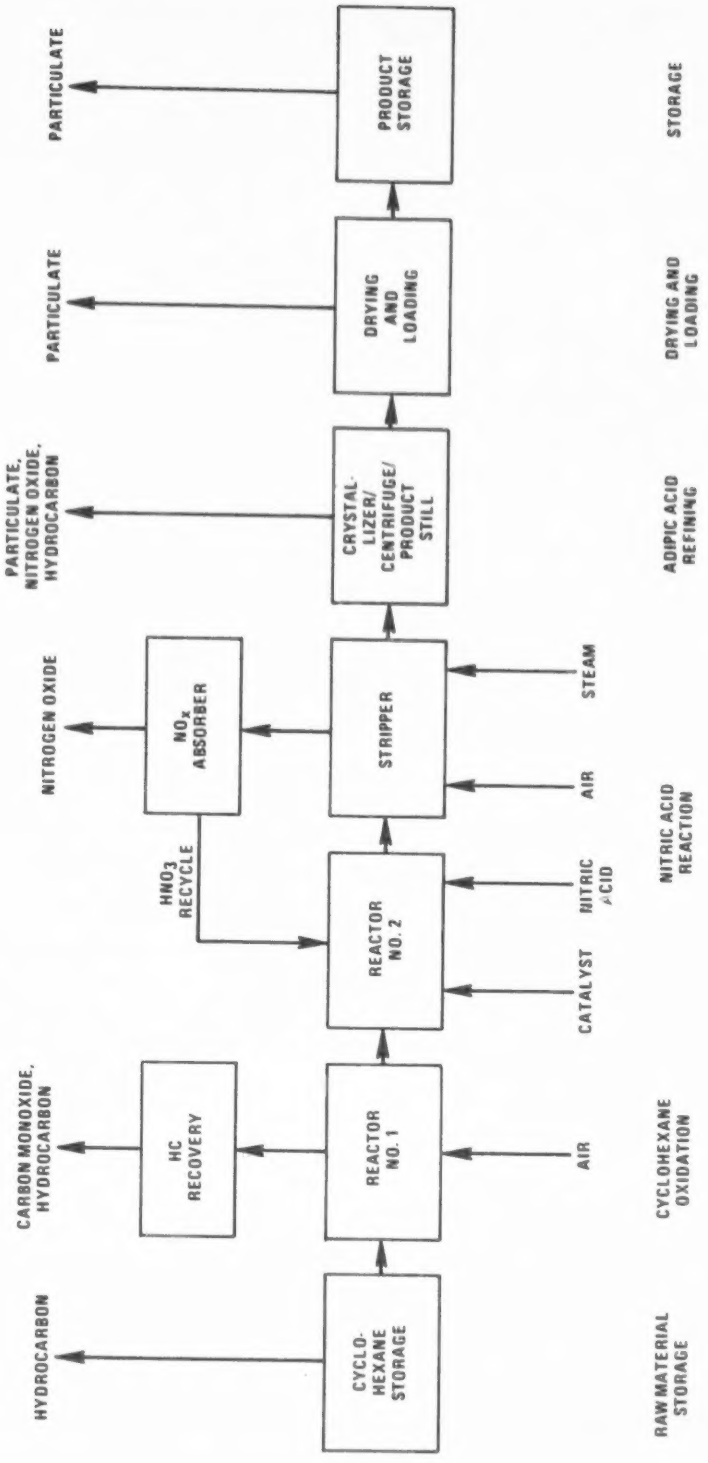

HYDROCARBON
CYCLOHEXANE STORAGE
RAW MATERIAL STORAGE
CARBON MONOXIDE, HYDROCARBON
HC RECOVERY
REACTOR NO. 1
AIR
CYCLOHEXANE OXIDATION
HNO3 RECYCLE
REACTOR NO. 2
CATALYST
NITRIC ACID
NITRIC ACID REACTION
NITROGEN OXIDE
NOx ABSORBER
STRIPPER
AIR
STEAM
PARTICULATE, NITROGEN OXIDE, HYDROCARBON
CRYSTAL-LIZER/ CENTRIFUGE/ PRODUCT STILL
ADIPIC ACID REFINING
PARTICULATE
DRYING AND LOADING
DRYING AND LOADING
PARTICULATE
PRODUCT STORAGE
STORAGE

Figure 5.1-1. General flow diagram of adipic acid manufacturing process.

Table 5.1-1. EMISSION FACTORS FOR ADIPIC ACID MANUFACTURE[1,a]
EMISSION FACTOR RATING: B

Process	Particulate		Nitrogen oxides[b]		Hydrocarbon		Carbon monoxide	
	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT
Raw material storage								
Uncontrolled	0	0	0	0	2.2	1.1	0	0
Cyclohexane oxidation								
Uncontrolled[c]	0	0	0	0	40	20	115	58
W/boiler	0	0	0	0	Neg[l]	Neg	1	0.5
W/thermal incinerator[d]	0	0	0	0	Neg	Neg	Neg	Neg
W/flaring[e]	0	0	0	0	4	2	12	6
W/carbon absorber[f]	0	0	0	0	2	1	115	58
W/scrubber plus boiler	0	0	0	0	Neg	Neg	Neg	Neg
Nitric acid reaction								
Uncontrolled[g]	0	0	53	27	0	0	0	0
W/water scrubber[h]	0	0	16	8	0	0	0	0
W/thermal reduction[i]	0	0	1	0.5	0	0	0	0
W/flaring or combustion[h]	0	0	16	8	0	0	0	0
Adipic acid refining[j]								
Uncontrolled[k]	<0.1	<0.1	0.6	0.3	0.5	0.3	0	0
Adipic acid drying, loading, and storage								
Uncontrolled[k]	0.8	0.4	0	0	0	0	0	0

[a] Emission factors are in units of pounds of pollutant per ton and kilograms of pollutant per metric ton of adipic acid produced.

[b] NO_x is in the form of NO and NO_2. Although large quantities of N_2O are also produced, N_2O is not considered a criteria pollutant and is not, therefore, included in these factors.

[c] Uncontrolled emission factors are after scrubber processing since hydrocarbon recovery using scrubbers is an integral part of adipic acid manufacturing.

[d] A thermal incinerator is assumed to reduce HC and CO emissions by approximately 99.99%.

[e] A flaring system is assumed to reduce HC and CO emissions by 90%.

[f] A carbon absorber is assumed to reduce HC emissions by 94% and to be ineffective in reducing CO emissions.

[g] Uncontrolled emission factors are after NO_x absorber since nitric acid recovery is an integral part of adipic acid manufacturing.

[h] Based on estimated 70% control.

[i] Based on estimated 97.5% control.

[j] Refining includes chilling, crystallization, centrifuging, and purification.

[k] Particulate emission factors are after baghouse control device.

[l] Negligible.

References for Section 5.1

1. Screening Study to Determine Need for Standards of Performance for New Adipic Acid Plants. GCA/Technology Division, Bedford, Mass. Prepared for Environmental Protection Agency, Research Triangle Park, N.C. under Contract No. 68-02-1316. July 1976.
2. Kirk-Othmer Encyclopedia of Chemical Technology. Adipic Acid. Vol. 1, 2nd Ed. New York, Interscience Encyclopedia, Inc. 1967. pp. 405-420.

5.2 AMMONIA

5.2.1 Process Description[1]

The manufacture of ammonia (NH_3) is accomplished primarily by the catalytic reaction of hydrogen and nitrogen at high temperatures and pressures. In a typical plant a hydrocarbon feed stream (usually natural gas) is desulfurized, mixed with steam, and catalytically reformed to carbon monoxide and hydrogen. Air is introduced into the secondary reformer to supply oxygen and provide a nitrogen to hydrogen ratio of 1 to 3. The gases then enter a two-stage shift converter that allows the carbon monoxide to react with water vapor to form carbon dioxide and hydrogen. The gas stream is next scrubbed to yield a gas containing less than 1 percent CO_2. A methanator may be used to convert quantities of unreacted CO to inert CH_4 before the gases, now largely nitrogen and hydrogen in a ratio of 1 to 3, are compressed and passed to the converter. Alternatively, the gases leaving the CO_2 scrubber may pass through a CO scrubber and then to the converter. The synthesis gases finally react in the converter to form ammonia.

5.2.2 Emissions and Controls[1]

When a carbon monoxide scrubber is used before sending the gas to the converter, the regenerator offgases contain significant amounts of carbon monoxide (73 percent) and ammonia (4 percent). This gas may be scrubbed to recover ammonia and then burned to utilize the CO fuel value.[2]

The converted ammonia gases are partially recycled, and the balance is cooled and compressed to liquefy the ammonia. The noncondensable portion of the gas stream, consisting of unreacted nitrogen, hydrogen, and traces of inerts such as methane, carbon monoxide, and argon, is largely recycled to the converter. To prevent the accumulation of these inerts, however, some of the noncondensable gases must be purged from the system.

The purge or bleed-off gas stream contains about 15 percent ammonia.[2] Another source of ammonia is the gases from the loading and storage operations. These gases may be scrubbed with water to reduce the atmospheric emissions. In addition, emissions of CO and ammonia can occur from plants equipped with CO-scrubbing systems. Emission factors are presented in Table 5.2-1.

Table 5.2-1. EMISSION FACTORS FOR AMMONIA MANUFACTURING WITHOUT CONTROL EQUIPMENT[a]
EMISSION FACTOR RATING: B

Type of source	Carbon monoxide		Hydrocarbons[b]		Ammonia	
	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT
Plants with methanator						
Purge gas[c]	Neg	Neg	90	45	3	1.5
Storage and loading[c]	–	–	–	–	200	100
Plants with CO absorber and regeneration system						
Regenerator exit[d]	200	100	–	–	7	3.5
Purge gas[c]	Neg	Neg	90	45	3	1.5
Storage and loading[c]	–	–	–	–	200	100

[a] References 2 and 3.

[b] Expressed as methane.

[c] Ammonia emissions can be reduced by 99 percent by passing through three stages of a packed-tower water scrubber. Hydrocarbons are not reduced.

[d] A two-stage water scrubber and incineration system can reduce these emissions to a negligible amount.

References for Section 5.2

1. Air Pollutant Emission Factors. Final Report. Resources Research, Incorporated. Reston, Virginia. Prepared for National Air Pollution Control Administration, Durham, N.C., under Contract Number CPA-22-69-119. April 1970.

2. Burns, W.E. and R.R. McMullan. No Noxious Ammonia Odor Here. Oil and Gas Journal. p. 129-131, February 25, 1967.

3. Axelrod, L.C. and T.E. O'Hare. Production of Synthetic Ammonia. New York, M. W. Kellogg Company. 1964.

5.3 CARBON BLACK

by Charles Mann

5.3.1 Process Description

Carbon black is produced by the reaction of a hydrocarbon fuel, such as oil or gas, with a limited supply of combustion air at temperatures of 2500 to 3000°F (1370 to 1650°C). The unburned carbon is collected as an extremely fine (10- to 400-nm diameter), black, fluffy particle. The three processes for producing carbon black are the furnace process, thermal process, and channel process. In 1973 the furnace process accounted for over 90 percent of production; the thermal process, 9 percent; and the channel process, less than 1 percent. The primary use for carbon black is for strengthening rubber products (mainly rubber tires); it is also used in printing inks, surface coatings, and plastics.

5.3.1.1 Furnace Process - Furnace black is produced by combustion of hydrocarbon feed in a refractory-lined furnace. Oil-fired furnaces now predominate. In this process (Figure 5.3-1) a heavy, aromatic oil feed is preheated and fed into the furnace with about half of the air required for complete combustion and a controlled amount of natural gas. The flue gases, which contain entrained carbon particles, are cooled to about 450°F (235°C) by passage through heat exchangers and water sprays. The carbon black is then separated from the gas stream, usually by a fabric filter. A cyclone for primary collection and particle agglomeration may precede the filter. A single collection system often serves a number of furnaces that are manifolded together.

The recovered carbon black is finished to a marketable product by pulverizing and wet pelletizing to increase bulk density. Water from the wet pelletizer is driven off in an indirect-fired rotary dryer. The dried pellets are then conveyed to bulk storage. Process yields range from 35 to 65 percent, depending on the particle size of the carbon black produced and the efficiency of the process. Furnace designs and operating characteristics influence the particle size of the oil black. Generally, yields are highest for large particle blacks and lowest for small particle sizes.

The older gas-furnace process is basically the same as the oil-furnace process except that a light hydrocarbon gas is the primary feedstock and furnace designs are different. Some oil may also be added to enrich the gas feed. Yields range from 10 to 30 percent, which is much less than in the oil process, and comparatively coarser particles (40- to 80-nm diameter compared to 20- to 50-nm diameter for oil-furnace blacks) are produced. Because of the scarcity of natural gas and the comparatively low efficiency of the gas process, carbon black production by this method has been declining.

5.3.1.2 Thermal Process - The thermal process is a cyclic operation in which natural gas is thermally decomposed to carbon particles, hydrogen, methane, and a mixture of other hydrocarbons. To start the cycle, natural gas is burned to heat a brick checkerwork in the process furnace to about 3000°F (1650°C). After this temperature is reached, the air supply is cut off, the furnace stack is closed, and natural gas is introduced into the furnace. The natural gas is decomposed by the heat from the hot bricks. When the bricks become cool, the natural gas flow is shut off. The effluent gases, containing the thermal black particles, are flushed out of the furnace and cooled by water sprays to about 250°F (125°C) before passing through cyclonic collectors and fabric filters, which recover the thermal black.

The effluent gases, consisting of about 90 percent hydrogen, 6 percent methane, and a mixture of other hydrocarbons, are cooled, compressed, and used as a fuel to reheat the furnaces. Normally, more than enough hydrogen is produced to make the thermal-black process self-sustaining, and the surplus hydrogen is used to fire boilers that supply process steam and electric power.

The collected thermal black is pulverized and pelletized to a final product in much the same manner as furnace black. Thermal-process yields are generally high (35 to 60 percent), but the relatively

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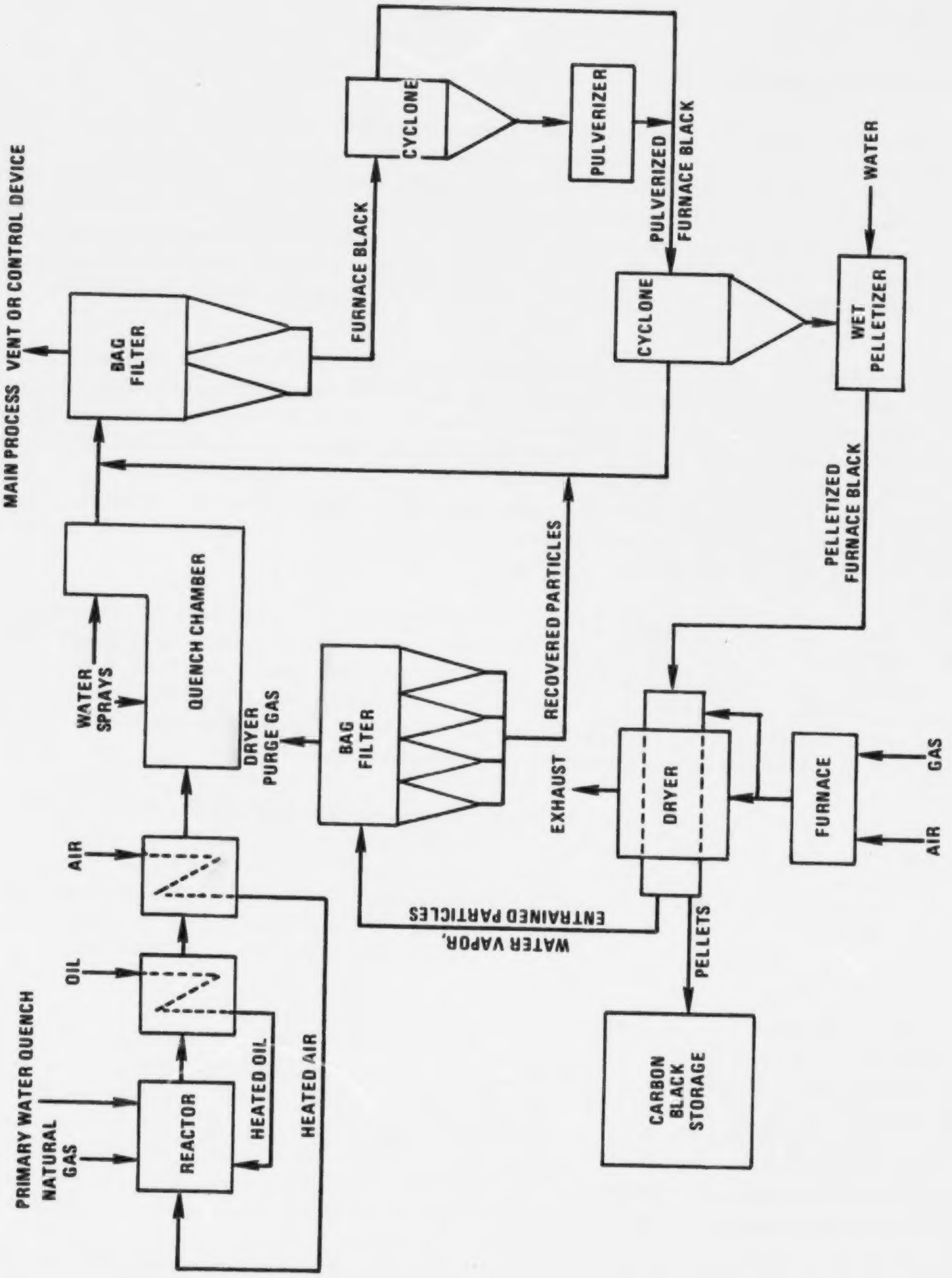

PRIMARY WATER QUENCH
NATURAL GAS
REACTOR
HEATED OIL
HEATED AIR
OIL
AIR
WATER SPRAYS
QUENCH CHAMBER
MAIN PROCESS VENT OR CONTROL DEVICE
BAG FILTER
FURNACE BLACK
CYCLONE
PULVERIZER
PULVERIZED FURNACE BLACK
CYCLONE
WATER
WET PELLETIZER
RECOVERED PARTICLES
DRYER PURGE GAS
BAG FILTER
PELLETIZED FURNACE BLACK
EXHAUST
DRYER
FURNACE
GAS
AIR
WATER VAPOR, ENTRAINED PARTICLES
PELLETS
CARBON BLACK STORAGE

Figure 5.3-1. Simplified flow diagram of carbon black production by the oil-fired furnace process.

coarse particles produced (180- to 470-nm diameter) do not have the strong reinforcing properties required for rubber products.

5.3.1.3 Channel Process - In the channel-black process, natural gas is burned with a limited air supply in long, low buildings. The flame from this burning impinges on long steel channel sections that swing continuously over the flame. Carbon black deposited on the channels is scraped off into collecting hoppers. The combustion gases, containing uncollected solid carbon, carbon monoxide, and other combustion products, are then vented directly from the building. Yields from the channel-black process are only 5 percent or less, but very fine particles are produced (10- to 30-nm diameter). Channel-black production has been declining steadily from its peak in the 1940's. Since 1974 no production of channel black has been reported.

5.3.2 Emissions and Controls

Emissions from carbon black manufacture include particulates, sulfur compounds, carbon monoxide, hydrocarbons, and nitrogen oxides. Trace amounts of polynuclear organic matter (POM) are also likely to be emitted. Emissions vary considerably from one process to another. Typical emission factors are given in Table 5.3-1.

The principal source of emissions in the furnace process is the main process vent. The vent stream consists of the reactor effluent plus quench water vapor vented from the carbon-black recovery system. Gaseous emissions vary considerably according to the grade of carbon black being produced. Hydrocarbon and CO emissions tend to be higher for small-particle black production. Sulfur compound emissions are a function of the feed sulfur content. Table 5.3-1 shows the normal emission ranges to be expected from these variations in addition to typical average values. Some particulate emissions may also occur from product transport, drier vents, the bagging and storage area, and spilled and leaked materials. Such emissions are generally negligible, however, because of the high efficiency of collection devices and sealed conveying systems used to prevent product loss.

Particulate emissions from the furnace-black process are controlled by fabric filters that recover the product from process and dryer vents. Particulate emissions control is therefore proportional to the efficiency of the product recovery system. Some producers may use water scrubbers on the dryer vent system.

Gaseous emissions from the furnace process may be controlled by CO boilers, incinerators, or flares. The pellet dryer combustion furnace, which is in essence a thermal incinerator, may also be employed in a control system. CO boilers, thermal incinerators, or combinations of these devices can achieve essentially complete oxidation of CO, hydrocarbons, and reduced sulfur compounds in the process flue gas. Particulate emissions may also be reduced by combustion of some of the carbon black particles; however, emissions of sulfur dioxide and nitrogen oxides are increased by these combustion devices.

Generally, emissions from the thermal process are negligible. Small amounts of nitrogen oxides and particulates may be emitted during the heating part of the process cycle when furnace stacks are open. Entrainment of carbon particles adhering to the checker brick may occur. Nitrogen oxides may be formed since high temperatures are reached in the furnaces. During the decomposition portion of the production cycle, the process is a closed system and no emissions would occur except through leaks.

Considerable emissions result from the channel process because of low efficiency of the process and the venting of the exhaust gas directly to the atmosphere. Most of the carbon input to the process is lost as CO, CO_2, hydrocarbons, and particulate.

Table 5.3-1. EMISSION FACTORS FOR CARBON BLACK MANUFACTURE[a]
EMISSION FACTOR RATING: B (OIL FURNACE PROCESS)
C (GAS FURNACE, CHANNEL, THERMAL PROCESSES)

Process	Particulate		Carbon monoxide		Hydrocarbons[b]		Nitrogen oxides		Hydrogen sulfide[c]		Sulfur oxides[c]	
	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT
Oil furnace process[d]												
Uncontrolled	6(2-16)[e]	3(1-8)[e]	2600(1400-3300)	1300(700-1650)	200(60-520)	100(30-260)	0.4	0.2	20S(10S-26S)	10S(5S-13S)	Neg	Neg
With CO boiler	3	1.5	10[f]	5[f]	3	1.5	6	3	0.2S	0.1S	40S	20S
With flare	3	1.5	130[g]	65[g]	10	5	6	3	0.2S	0.1S	40S	20S
Gas furnace process[h]	10	5	5300(4200-6400)	2650(2100-3200)	1,800	900	-	-	Neg	Neg	Neg	Neg
Channel process[i]	2,300	1,150	33,500	16,750	11,500	5,750	-	-	Neg	Neg	Neg	Neg
Thermal process[j]	Neg	Neg	Neg	Neg	Neg	Neg	Neg	Neg	Neg	Neg	Neg	Neg

[a] Expressed in terms of pounds per ton and kilograms per metric ton of carbon black product.

[b] As methane. Actual composition of emissions is 50-75% acetylene and the remainder methane.

[c] S is the weight percent sulfur in the feed. Emission factor based on a 50% yield of carbon in the feed to carbon black product and an average 50% conversion of sulfur in the feed to H_2S.

[d] References 5 and 6.

[e] Based on fabric filter collection efficiency of 99.5 to 99.9%.

[f] Based on over 99% control of CO. Thermal incinerators could also be expected to achieve 99% oxidation of CO. (Reference 6).

[g] Based on 95% oxidation of CO (Reference 6).

[h] References 1 and 2.

[i] References 1 and 2.

[j] Emissions data are not available, but no significant emissions are believed to occur.

References for Section 5.3

1. Air Pollutant Emission Factors. Final Report. Resources Research, Incorporated. Reston, Virginia. Prepared for National Air Pollution Control Administration, Durham, N.C., under Contract Number CPA-22-69-119. April 1970.

2. Drogin, I. Carbon Black. J. Air Pol. Control Assoc. 18:216-228, April 1968.

3. Cox, J.T. High Quality, High Yield Carbon Black. Chem. Eng. 57:116-117, June 1950.

4. Reinke, R.A. and T.A. Ruble. Oil Black. Ind. Eng. Chem. 44:685-694, April 1952.

5. Engineering and Cost Study of Air Pollution Control for the Petrochemical Industry, Volume 1: Carbon Black Manufacture by the Furnace Process. Houdry Division, Air Products and Chemicals, Incorporated. Publication Number EPA-450/3-73-006a. June 1974.

6. Hustvedt, Kent C., Leslie B. Evans, and William M. Vatavuk. Standards Support and Environmental Impact Statement, An Investigation of the Best Systems of Emission Reduction for Furnace Process Carbon Black Plants in the Carbon Black Industry. U.S. Environmental Protection Agency, Research Triangle Park, N.C. April 1976.

7. Carbon Black (Oil Black). Continental Carbon Company. Hydrocarbon Processing. 52:111. November 1973.

5.4 CHARCOAL

5.4.1 Process Description[1]

Charcoal is generally manufactured by means of pyrolysis, or destructive distillation, of wood waste from members of the deciduous hardwood species. In this process, the wood is placed in a retort where it is externally heated for about 20 hours at 500 to 700°F (260 to 370°C). Although the retort has air intakes at the bottom, these are only used during start-up and thereafter are closed. The entire distillation cycle takes approximately 24 hours, the last 4 hours being an exothermic reaction. Four units of hardwood are required to produce one unit of charcoal.

5.4.2 Emissions and Controls[1]

In the pyrolysis of wood, all the gases, tars, oils, acids, and water are driven off, leaving virtually pure carbon. All of these except the gas, which contains methane, carbon monoxide, carbon dioxide, nitrogen oxides, and aldehydes, are useful by-products if recovered. Unfortunately, economics has rendered the recovery of the distillate by-products unprofitable, and they are generally permitted to be discharged to the atmosphere. If a recovery plant is utilized, the gas is passed through water-cooled condensers. The condensate is then refined while the remaining cool, noncondensable gas is discharged to the atmosphere. Gaseous emissions can be controlled by means of an afterburner because the unrecovered by-products are combustible. If the afterburner operates efficiently, no organic pollutants should escape into the atmosphere. Emission factors for the manufacture of charcoal are shown in Table 5.4-1.

Table 5.4-1. EMISSION FACTORS FOR CHARCOAL MANUFACTURING[a,d]
EMISSION FACTOR RATING: C

Pollutant	Type of operation			
	With chemical recovery plant		Without chemical recovery plant	
	lb/ton	kg/MT	lb/ton	kg/MT
Particulate (tar, oil)	–	–	400	200
Carbon monoxide	320[b]	160[b]	320[b]	160[b]
Hydrocarbons[c]	100[b]	50[b]	100[b]	50[b]
Crude methanol	–	–	152	76
Acetic acid	–	–	232	116
Other gases (HCHO, N_2 NO)	60	30	60[b]	30[b]

[a] Calculated values based on data in Reference 2.
[b] Emissions are negligible if afterburner is used.
[c] Expressed as methane.
[d] Emission factors expressed in units of tons of charcoal produced.

References for Section 5.4

1. Air Pollutant Emission Factors. Final Report. Resources Research, Inc. Reston, Va. Prepared for National Air Pollution Control Administration, Durham, N.C., under Contract Number CPA-22-69-119. April 1970.

2. Shreve, R.N. Chemical Process Industries, 3rd Ed. New York, McGraw-Hill Book Company. 1967. p. 619.

5.5 CHLOR–ALKALI

5.5.1 Process Description[1]

Chlorine and caustic are produced concurrently by the electrolysis of brine in either the diaphragm or mercury cell. In the diaphragm cell, hydrogen is liberated at the cathode and a diaphragm is used to prevent contact of the chlorine produced at the anode with either the alkali hydroxide formed or the hydrogen. In the mercury cell, liquid mercury is used as the cathode and forms an amalgam with the alkali metal. The amalgam is removed from the cell and is allowed to react with water in a separate chamber, called a denuder, to form the alkali hydroxide and hydrogen.

Chlorine gas leaving the cells is saturated with water vapor and then cooled to condense some of the water. The gas is further dried by direct contact with strong sulfuric acid. The dry chlorine gas is then compressed for in-plant use or is cooled further by refrigeration to liquefy the chlorine.

Caustic as produced in a diaphragm-cell plant leaves the cell as a dilute solution along with unreacted brine. The solution is evaporated to increase the concentration to a range of 50 to 73 percent; evaporation also precipitates most of the residual salt, which is then removed by filtration. In mercury-cell plants, high-purity caustic can be produced in any desired strength and needs no concentration.

5.5.2 Emissions and Controls[1]

Emissions from diaphragm- and mercury-cell chlorine plants include chlorine gas, carbon dioxide, carbon monoxide, and hydrogen. Gaseous chlorine is present in the blow gas from liquefaction, from vents in tank cars and tank containers during loading and unloading, and from storage tanks and process transfer tanks. Other emissions include mercury vapor from mercury cathode cells and chlorine from compressor seals, header seals, and the air blowing of depleted brine in mercury-cell plants.

Chlorine emissions from chlor-alkali plants may be controlled by one of three general methods: (1) use of the gas in other plant processes, (2) neutralization in alkaline scrubbers, and (3) recovery of chlorine from effluent gas streams. The effect of specific control practices is shown to some extent in the table on emission factors (Table 5.5-1).

References for Section 5.5

1. Atmospheric Emissions from Chlor-Alkali Manufacture. U.S. EPA, Air Pollution Control Office. Research Triangle Park, N.C. Publication Number AP-80. January 1971.

2. Duprey, R.L. Compilation of Air Pollutant Emission Factors. U.S. DHEW, PHS, National Center for Air Pollution Control. Durham, N.C. PHS Publication Number 999-AP-42. 1968. p. 49.

Table 5.5-1. EMISSION FACTORS FOR CHLOR-ALKALI PLANTS[a]
EMISSION FACTOR RATING: B

Type of source	Chlorine gas	
	lb/100 tons	kg/100 MT
Liquefaction blow gases		
Diaphragm cell, uncontrolled	2,000 to 10,000	1,000 to 5,000
Mercury cell[b], uncontrolled	4,000 to 16,000	2,000 to 8,000
Water absorber	25 to 1,000	12.5 to 500
Caustic or lime scrubber	1	0.5
Loading of chlorine		
Tank car vents	450	225
Storage tank vents	1,200	600
Air-blowing of mercury-cell brine	500	250

[a] References 1 and 2.

[b] Mercury cells lose about 1.5 pounds mercury per 100 tons (0.75 kg/100 MT) of chlorine liquefied.

5.6 EXPLOSIVES

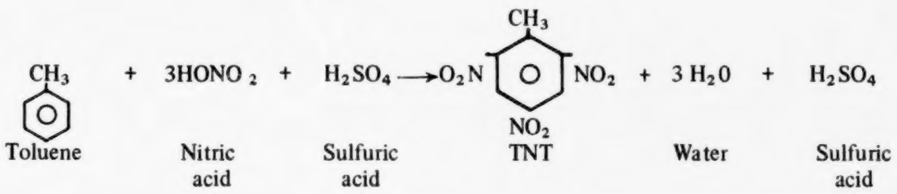
by Charles Mann

5.6.1 General[1]

An explosive is a material that, under the influence of thermal or mechanical shock, decomposes rapidly and spontaneously with the evolution of large amounts of heat and gas. Explosives fall into two major categories: high explosives and low explosives. High explosives are further subdivided into initiating or primary high explosives and secondary high explosives. Initiating high explosives are very sensitive and are generally used in small quantities in detonators and percussion caps to set off larger quantities of secondary high explosives. Secondary high explosives, chiefly nitrates, nitro compounds, and nitramines, are much less sensitive to mechanical or thermal shock, but explode with great violence when set off by an initiating explosive. The chief secondary high explosives manufactured for commercial and military use are ammonium nitrate blasting agents and 2.4. 6,-trinitrotoluene (TNT). Low explosives, such as black powder and nitrocellulose, undergo relatively slow autocombustion when set off and evolve large volumes of gas in a definite and controllable manner. A multitude of different types of explosives are manufactured. As examples of the production of a high explosive and a low explosive, the production of TNT and nitrocellulose are discussed in this section.

5.6.2 TNT Production [1-3]

TNT may be prepared by either a continuous process or a batch, three-stage nitration process using toluene, nitric acid, and sulfuric acid as raw materials. In the batch process, a mixture of oleum (fuming sulfuric acid) and nitric acid that has been concentrated to a 97 percent solution is used as the nitrating agent. The overall reaction may be expressed as:



(1)

Spent acid from the nitration vessels is fortified with make-up 60 percent nitric acid before entering the next nitrator. Fumes from the nitration vessels are collected and removed from the exhaust by an oxidation-absorption system. Spent acid from the primary nitrator is sent to the acid recovery system in which the sulfuric and nitric acid are separated. The nitric acid is recovered as a 60 percent solution, which is used for refortification of spent acid from the second and third nitrators. Sulfuric acid is concentrated in a drum concentrator by boiling water out of the dilute acid. The product from the third nitration vessel is sent to the wash house at which point asymmetrical isomers and incompletely nitrated compounds are removed by washing with a solution of sodium sulfite and sodium hydrogen sulfite (Sellite). The wash waste (commonly called red water) from the purification process is discharged directly as a liquid waste stream, is collected and sold, or is concentrated to a slurry and incinerated in rotary kilns. The purified TNT is solidified, granulated, and moved to the packing house for shipment or storage. A schematic diagram of TNT production by the batch process is shown in Figure 5.6-1.

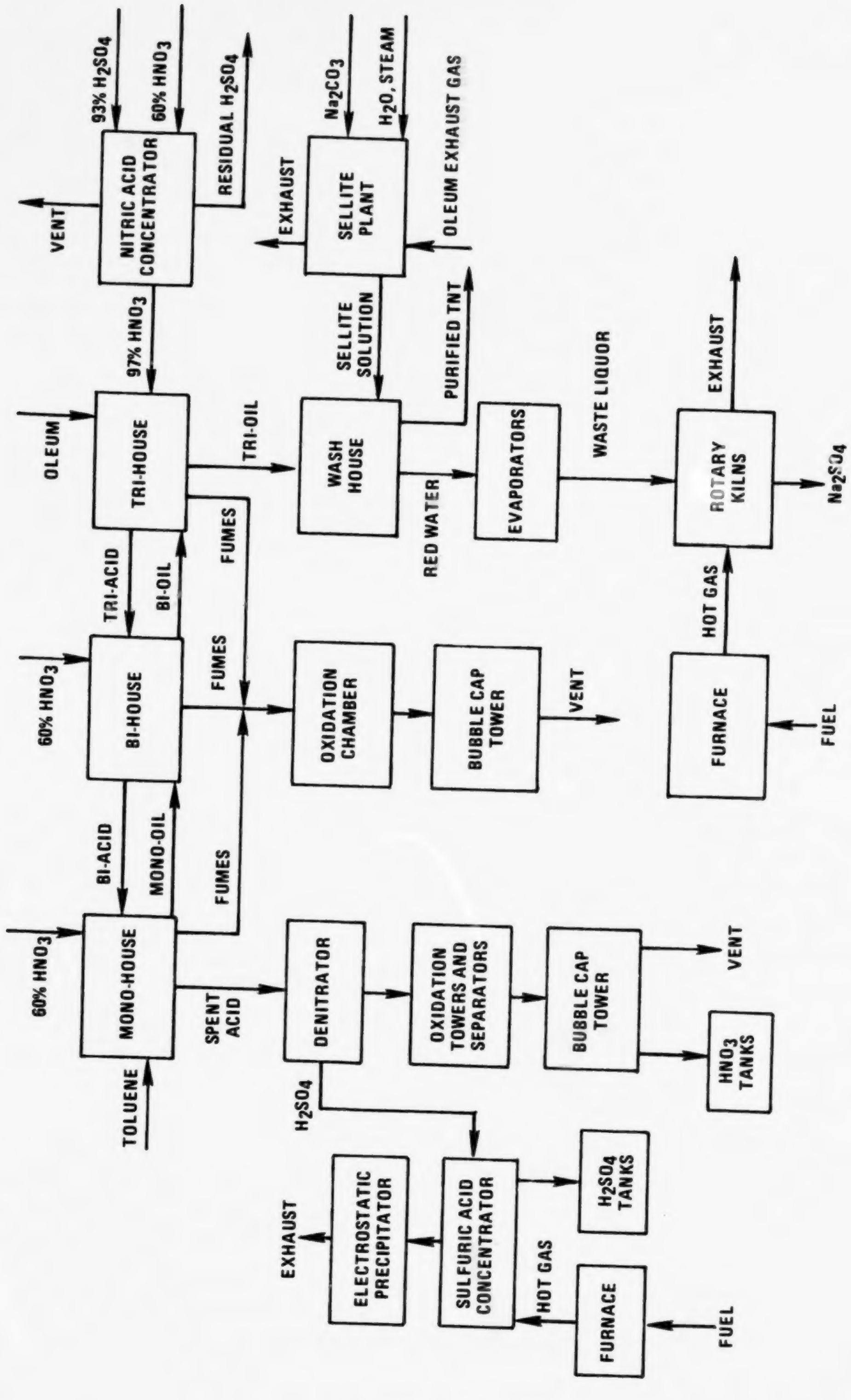

93% H_2SO_4
60% HNO_3
RESIDUAL H_2SO_4
VENT
NITRIC ACID CONCENTRATOR
97% HNO_3
Na_2CO_3
H_2O, STEAM
OLEUM EXHAUST GAS
EXHAUST
SELLITE PLANT
SELLITE SOLUTION
PURIFIED TNT
OLEUM
TRI-HOUSE
TRI-OIL
WASH HOUSE
RED WATER
EVAPORATORS
WASTE LIQUOR
EXHAUST
ROTARY KILNS
Na_2SO_4
TRI-ACID
BI-OIL
FUMES
60% HNO_3
BI-HOUSE
FUMES
OXIDATION CHAMBER
BUBBLE CAP TOWER
VENT
HOT GAS
FURNACE
FUEL
BI-ACID
MONO-OIL
FUMES
60% HNO_3
MONO-HOUSE
TOLUENE
SPENT ACID
DENITRATOR
OXIDATION TOWERS AND SEPARATORS
BUBBLE CAP TOWER
VENT
HNO_3 TANKS
H_2SO_4
SULFURIC ACID CONCENTRATOR
H_2SO_4 TANKS
ELECTROSTATIC PRECIPITATOR
EXHAUST
HOT GAS
FURNACE
FUEL

Figure 5.6-1. Flow diagram of typical batch process TNT plant.

5.6.3 Nitrocellulose Production [1]

Nitrocellulose is prepared by the batch-type "mechanical dipper" process. Cellulose, in the form of cotton linters, fibers, or specially prepared wood pulp, is purified, bleached, dried, and sent to a reactor (niter pot) containing a mixture of concentrated nitric acid and a dehydrating agent such as sulfuric acid, phosphoric acid, or magnesium nitrate. The overall reaction may be expressed as:

$$\underset{\text{Cellulose}}{C_6H_7O_2(OH)_3} + \underset{\substack{\text{Nitric}\\\text{acid}}}{3HONO_2} + \underset{\substack{\text{Sulfuric}\\\text{acid}}}{H_2SO_4} \longrightarrow \underset{\text{Nitrocellulose}}{C_6H_7O_2(ONO_2)_3} + \underset{\text{Water}}{3\,H_2O} + \underset{\substack{\text{Sulfuric}\\\text{acid}}}{H_2SO_4} \qquad (2)$$

When nitration is complete, the reaction mixtures are centrifuged to remove most of the spent acid. The spent acid is fortified and reused or otherwise disposed of. The centrifuged nitrocellulose undergoes a series of water washings and boiling treatments for purification of the final product.

5.6.4 Emissions and Controls[2,3,5]

The major emissions from the manufacture of explosives are nitrogen oxides and acid mists, but smaller amounts of sulfuric oxides and particulates may also be emitted. Emissions of nitrobodies (nitrated organic compounds) may also occur from many of the TNT process units. These compounds cause objectionable odor problems and act to increase the concentration of acid mists. Emissions of sulfur oxides and nitrogen oxides from the production of nitric acid and sulfuric acid used for explosives manufacturing can be considerable. It is imperative to identify all processes that may take place at an explosives plant in order to account for all sources of emissions. Emissions from the manufacture of nitric and sulfuric acid are discussed in other sections of this publication.

In the manufacture of TNT, vents from the fume recovery system, sulfuric acid concentrators, and nitric acid concentrators are the principal sources of emissions. If open burning or incineration of waste explosives is practiced, considerable emissions may result. Emissions may also result from the production of Sellite solution and the incineration of red water. Many plants, however, now sell the red water to the paper industry where it is of economic importance.

Principal sources of emissions from nitrocellulose manufacture are from the reactor pots and centrifuges, spent acid concentrators, and boiling tubs used for purification.

The most important factor affecting emissions from explosives manufacture is the type and efficiency of the manufacturing process. The efficiency of the acid and fume recovery systems for TNT manufacture will directly affect the atmospheric emissions. In addition, the degree to which acids are exposed to the atmosphere during the manufacturing process affects the NO_X and SO_X emissions. For nitrocellulose production, emissions are influenced by the nitrogen content and the desired quality of the final product. Operating conditions will also affect emissions. Both TNT and nitrocellulose are produced in batch processes. Consequently, the processes may never reach steady state and emission concentrations may vary considerably with time. Such fluctuations in emissions will influence the efficiency of control methods. Several measures may be taken to reduce emissions from explosives manufacturing. The effects of various control devices and process changes upon emissions, along with emission factors for explosives manufacturing, are shown in Table 5.6-1. The emission factors are all related to the amount of product produced and are appropriate for estimating long-term emissions or for evaluating plant operation at full production conditions. For short time periods or for plants with intermittent operating schedules, the emission factors in Table 5.6-1 should be used with caution, because processes not associated with the nitration step are often not in operation at the same time as the nitration reactor.

Table 5.6-1. EMISSION FACTORS FOR
EMISSION FACTOR

Type of process	Particulates		Sulfur oxides (SO_2)	
	lb/ton	kg/MT	lb/ton	kg/MT
TNT - batch process[b]				
Nitration reactors				
Fume recovery	–	–	–	–
Acid recovery	–	–	–	–
Nitric acid concentrators	–	–	–	–
Sulfuric acid concentrators[c]				
Electrostatic precipitator (exit)	–	–	14(4-40)	7(2-20)
Electrostatic precipitator with scrubber[d]	–	–	Neg.	Neg.
Red water incinerator				
Uncontrolled[e]	25(0.03-126)	12.5(0.015-63)	2(0.05-3.5)	1(0.025-1.75)
Wet scrubber[f]	1	0.5	2(0.05-3.5)	1(0.025-1.75)
Sellite exhaust	–	–	59(0.01-177)	29.5(0.005-88)
TNT - continuous process[g]				
Nitration reactors				
Fume recovery	–	–	–	–
Acid recovery	–	–	–	–
Red water incinerator	0.25(0.03-0.05)	0.13(0.015-0.025)	0.24(0.05-0.43)	0.12(0.025-0.22)
Nitrocellulose[g]				
Nitration reactors[h]	–	–	1.4(0.8-2)	0.7(0.4-1)
Nitric acid concentrator	–	–	–	–
Sulfuric acid concentrator	–	–	68(0.4-135)	34(0.2-67)
Boiling tubs	–	–	–	–

[a] For some processes considerable variations in emissions have been reported. The average of the values reported is shown first, with the ranges given in parentheses. Where only one number is given, only one source test was available.

[b] Reference 5.

[c] Acid mist emissions influenced by nitrobody levels and type of fuel used in furnace.

[d] No data available for NO_x emissions after the scrubber. It is assumed that NO_x emissions are unaffected by the scrubber.

EXPLOSIVES MANUFACTURING[a]
RATING: C

Nitrogen oxides (NO_2)		Nitric acid mist (100% HNO_3)		Sulfuric acid mist (100% H_2SO_4)	
lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT
25(6-38)	12.5(3-19)	1(0.3-1.9)	0.5(0.5-0.95)	–	–
55(1-136)	27.5(0.5-68)	92(0.01-275)	46(0.005-137)	–	–
37(16-72)	18.5(8-36)	–	–	9(0.3-27)	4.5(0.15-13.5)
40(2-80)	20(1-40)	–	–	65(1-188)	32.5(0.5-94)
40(2-80)	20(1-40)	–	–	5(4-6)	2.5(2-3)
26(1.5-101)	13(0.75-50)	–	–	–	–
5	2.5	–	–	–	–
–	-	–	–	6(0.6-16)	3(0.3-8)
8(6.7-10)	4(3.35-5)	1(0.3-1.9)	0.5(0.15-0.95)	–	–
3(1-4.5)	1.5(0.5-2.25)	0.02(0.01-0.03)	0.01(0.005-0.015)	–	–
7(6.1-8.4)	3.5(3-4.2)	–	–	–	–
14(3.7-34)	7(1.85-17)	19(0.5-36)	9.5(0.25-18)	–	–
14(10-18)	7(5-9)	–	–	–	–
		–	–	0.3	0.3
2	1	–	–	–	–

[e] Use low end of range for modern, efficient units and high end of range for older, less efficient units.

[f] Apparent reductions in NO_x and particulate after control may not be significant because these values are based on only one test result.

[g] Reference 4.

[h] For product with low nitrogen content (12 percent), use high end of range. For products with higher nitrogen content, use lower end of range.

References for Section 5.6

1. Shreve, R.N. Chemical Process Industries, 3rd Ed. New York, McGraw-Hill Book Company, 1967. p. 383-395.
2. Unpublished data on emissions from explosives manufacturing, National Air Pollution Control Administration, Office of Criteria and Standards, Durham, N.C. June 1970.
3. Higgins, F.B., Jr., et al. Control of Air Pollution From TNT Manufacturing. (Presented at 60th annual meeting of Air Pollution Control Association. Cleveland. June 1967. Paper 67-111.)
4. Air Pollution Engineering Source Sampling Surveys, Radford Army Ammunition Plant. U.S. Army Environmental Hygiene Agency, Edgewood Arsenal, Md.
5. Air Pollution Engineering Source Sampling Surveys, Volunteer Army Ammunition Plant and Joliet Army Ammunition Plant. U.S. Army Environmental Hygiene Agency, Edgewood Arsenal, Md.

5.7 HYDROCHLORIC ACID

Hydrochloric acid is manufactured by a number of different chemical processes. Approximately 80 percent of the hydrochloric acid, however, is produced by the by-product hydrogen chloride process, which will be the only process discussed in this section. The synthesis process and the Mannheim process are of secondary importance.

5.7.1 Process Description[1]

By-product hydrogen chloride is produced when chlorine is added to an organic compound such as benzene, toluene, and vinyl chloride. Hydrochloric acid is produced as a by-product of this reaction. An example of a process that generates hydrochloric acid as a by-product is the direct chlorination of benzene. In this process benzene, chlorine, hydrogen, air, and some trace catalysts are the raw materials that produce chlorobenzene. The gases from the reaction of benzene and chlorine consist of hydrogen chloride, benzene, chlorobenzenes, and air. These gases are first scrubbed in a packed tower with a chilled mixture of monochlorobenzene and dichlorobenzene to condense and recover any benzene or chlorobenzene. The hydrogen chloride is then absorbed in a falling film absorption plant.

5.7.2 Emissions

The recovery of the hydrogen chloride from the chlorination of an organic compound is the major source of hydrogen chloride emissions. The exit gas from the absorption or scrubbing system is the actual source of the hydrogen chloride emitted. Emission factors for hydrochloric acid produced as by-product hydrogen chloride are presented in Table 5.7-1.

Table 5.7-1. EMISSION FACTORS FOR HYDROCHLORIC ACID MANUFACTURING[a]
EMISSION FACTOR RATING: B

Type of process	Hydrogen chloride emissions	
	lb/ton	kg/MT
By-product hydrogen chloride		
With final scrubber	0.2	0.1
Without final scrubber	3	1.5

[a] Reference 1.

Reference for Section 5.7

1. Atmospheric Emissions from Hydrochloric Acid Manufacturing Processes. U.S. DHEW, PHS, CPEHS, National Air Pollution Control Administration. Durham, N.C. Publication Number AP-54. September 1969.

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5.8 HYDROFLUORIC ACID

5.8.1 Process Description[1]

All hydrofluoric acid in the United States is currently produced by the reaction of acid-grade fluorspar with sulfuric acid for 30 to 60 minutes in externally fired rotary kilns at a temperature of 400° to 500°F (204° to 260°C).[2,3,4] The resulting gas is then cleaned, cooled, and absorbed in water and weak hydrofluoric acid to form a strong acid solution. Anhydrous hydrofluoric acid is formed by distilling 80 percent hydrofluoric acid and condensing the gaseous HF which is driven off.

5.8.2 Emissions and Controls[1]

Air pollutant emissions are minimized by the scrubbing and absorption systems used to purify and recover the HF. The initial scrubber utilizes concentrated sulfuric acid as a scrubbing medium and is designed to remove dust, SO_2, SO_3, sulfuric acid mist, and water vapor present in the gas stream leaving the primary dust collector. The exit gases from the final absorber contain small amounts of HF, silicon tetrafluoride (SiF_4), CO_2, and SO_2 and may be scrubbed with a caustic solution to reduce emissions further. A final water ejector, sometimes used to draw the gases through the absorption system, will reduce fluoride emissions. Dust emissions may also result from raw fluorspar grinding and drying operations. Table 5.8-1 lists the emission factors for the various operations.

Table 5.8-1. EMISSION FACTORS FOR HYDROFLUORIC ACID MANUFACTURING[a]
EMISSION FACTOR RATING: C

Type of operation	Fluorides		Particulates	
	lb/ton acid	kg/MT acid	lb/ton fluorspar	kg/MT fluorspar
Rotary kiln				
Uncontrolled	50	25	–	–
Water scrubber	0.2	0.1	–	–
Grinding and drying of fluorspar	–	–	20[b]	10[b]

[a] References 2 and 5.

[b] Factor given for well-controlled plant.

References for Section 5.8

1. Air Pollutant Emission Factors. Final Report. Resources Research Inc., Reston, Va. Prepared for National Air Pollution Control Administration, Durham, N.C., under Contract Number CPA-22-69-119. April 1970.

2. Rogers, W.E. and K. Muller. Hydrofluoric Acid Manufacture. Chem. Eng. Progr. *59*:85-88, May 1963.

3. Heller, A.N., S.T. Cuffe, and D.R. Goodwin. Inorganic Chemical Industry. In: Air Pollution Engineering Manual. Danielson, J.A. (ed.). U.S. DHEW, PHS, National Center for Air Pollution Control. Cincinnati, Ohio. Publication Number 999-AP-40. 1967. p. 197-198.

4. Hydrofluoric Acid. Kirk-Othmer Encyclopedia of Chemical Technology, Vol. 9. New York, John Wiley and Sons, Inc. 1964. p. 444-485.

5. Private Communication between Resources Research, Incorporated, and E.I. DuPont de Nemours and Company. Wilmington, Delaware. January 13, 1970.

5.9 NITRIC ACID

Revised by William Vatavuk

5.9.1 Process Description

5.9.1.1 Weak Acid Production[1] - Nearly all the nitric acid produced in the United States is manufactured by the high-pressure catalytic oxidation of ammonia (Figure 5.9-1). Typically, this process consists of three steps, each of which corresponds to a distinct chemical reaction. First, a 1:9 ammonia-air mixture is oxidized at high temperature and pressure (6.4 to 9.2 atmospheres), as it passes through a platinum-rhodium catalyst, according to the reaction:

$$\underset{\text{Ammonia}}{4NH_3} + \underset{\text{Oxygen}}{5O_2} \rightarrow \underset{\text{Nitric oxide}}{4NO} + \underset{\text{Water}}{6H_2O} \tag{1}$$

After the process stream is cooled to 100°F (38°C) or less by passage through a cooler-condenser, the nitric oxide reacts with residual oxygen:

$$2NO + O_2 \rightarrow \underset{\text{Nitrogen dioxide}}{2NO_2} \rightleftarrows \underset{\text{Nitrogen tetroxide}}{N_2O_4} \tag{2}$$

Finally, the gases are introduced into a bubble-cap plate absorption column where they are contacted with a countercurrent stream of water. The exothermic reaction that occurs is:

$$3NO_2 + H_2O \rightarrow \underset{\substack{\text{Nitric acid} \\ \text{50 to 70\% aqueous}}}{2HNO_3} + NO \tag{3}$$

The production of nitric oxide in reaction (3) necessitates the introduction of a secondary air stream into the column to effect its oxidation to nitrogen dioxide, thereby perpetuating the absorption operation.

The spent gas flows from the top of the absorption tower to an entrainment separator for acid mist removal, through the ammonia oxidation unit for energy absorption from the ammonia stream, through an expander for energy recovery, and finally to the stack. In most plants the stack gas is treated before release to the atmosphere by passage through either a catalytic combustor or, less frequently, an alkaline scrubber.

5.9.1.2 High-Strength Acid Production[1] - To meet requirements for high strength acid, the 50 to 70 percent acid produced by the pressure process is concentrated to 95 to 99 percent at approximately atmospheric pressure. The concentration process consists of feeding strong sulfuric acid and 60 percent nitric acid to the top of a packed column where it is contacted by an ascending stream of weak acid vapor, resulting in the dehydration of the latter. The concentrated acid vapor that leaves the column passes to a bleacher and countercurrent condenser system to effect condensation of the vapors and separation of the small amounts of nitric oxides and oxygen that form as dehydration by-products. These by-products then flow to an absorption column where the nitric oxide mixes with auxiliary air to form nitrogen dioxide, which is, in turn, recovered as weak nitric acid. Finally, unreacted gases are vented to the atmosphere from the top of the column.

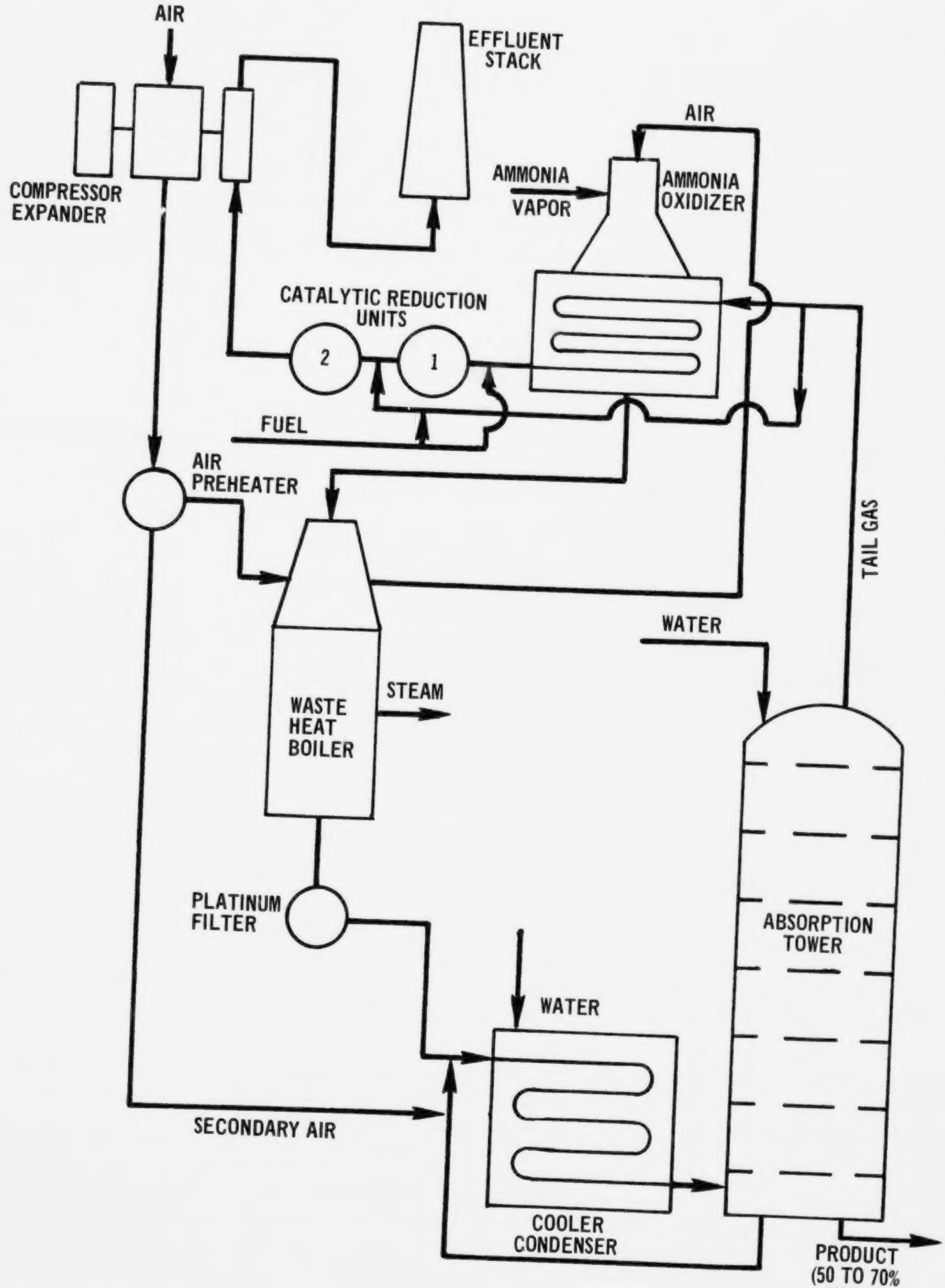

AIR
EFFLUENT STACK
COMPRESSOR EXPANDER
AIR
AMMONIA VAPOR
AMMONIA OXIDIZER
CATALYTIC REDUCTION UNITS
2
1
FUEL
AIR PREHEATER
TAIL GAS
WATER
STEAM
WASTE HEAT BOILER
PLATINUM FILTER
ABSORPTION TOWER
WATER
SECONDARY AIR
COOLER CONDENSER
PRODUCT (50 TO 70% HNO3)

Figure 5.9-1. Flow diagram of typical nitric acid plant using pressure process.

5.9.2 Emissions and Controls[1-3]

The emissions derived from nitric acid manufacture consist primarily of nitric oxide, which accounts for visible emissions; nitrogen dioxide; and trace amounts of nitric acid mist. By far, the major source of nitrogen oxides is the tail gas from the acid absorption tower (Table 5.9-1). In general, the quantity of NO_x emissions is directly related to the kinetics of the nitric acid formation reaction.

The specific operating variables that increase tail gas NO_x emissions are: (1) insufficient air supply, which results in incomplete oxidation of NO; (2) low pressure in the absorber; (3) high temperature in the cooler-condenser and absorber; (4) production of an excessively high-strength acid; and (5) operation at high throughput rates, which results in decreased residence time in the absorber.

Aside from the adjustment of these variables, the most commonly used means for controlling emissions is the catalytic combustor. In this device, tail gases are heated to ignition temperature, mixed with fuel (natural gas, hydrogen, or a mixture of both), and passed over a catalyst. The reactions that occur result in the successive reduction of NO_2 to NO and, then, NO to N_2. The extent of reduction of NO_2 to N_2 in the combustor is, in turn, a function of plant design, type of fuel used, combustion temperature and pressure, space velocity through the combustor, type and amount of catalyst used, and reactant concentrations (Table 5.9-1).

Comparatively small amounts of nitrogen oxides are also lost from acid concentrating plants. These losses (mostly NO_2) occur from the condenser system, but the emissions are small enough to be easily controlled by the installation of inexpensive absorbers.

Table 5.9-1. NITROGEN OXIDE EMISSIONS FROM NITRIC ACID PLANTS[a]
EMISSION FACTOR RATING: B

Type of control	Control efficiency, %	Emissions (NO_2)[b] lb/ton acid	kg/MT acid
Weak acid			
Uncontrolled	0	50 to 55[c]	25.0 to 27.5
Catalytic combustor (natural gas fired)	78 to 97	2 to 7[d]	1.0 to 3.5
Catalytic combustor (hydrogen fired)	97 to 99.8	0.0 to 1.5	0.0 to 0.75
Catalytic combustor (75% hydrogen, 25% natural gas fired)	98 to 98.5	0.8 to 1.1	0.4 to 0.55
High-strength acid	–	0.2 to 5.0	0.1 to 2.5

[a] References 1 and 2.

[b] Based on 100 percent acid production.

[c] Range of values taken from four plants measured at following process conditions: production rate, 120 tons (109 MT) per day (100 percent rated capacity); absorber exit temperature, 90° F (32° C); absorber exit pressure, 7.8 atmospheres; acid strength, 57 percent. Under different conditions, values can vary from 43 to 57 lb/ton (21.5 to 28.5 kg/MT).

[d] To present a more realistic picture, ranges of values were used instead of averages.

Acid mist emissions do not occur from a properly operated plant. The small amounts that may be present in the absorber exit gas stream are removed by a separator or collector prior to entering the catalytic combustor or expander.

Finally, small amounts of nitrogen dioxide are lost during the filling of storage tanks and tank cars.

Nitrogen oxide emissions (expressed as NO_2) are presented for weak nitric acid plants in table 5.9-1. The emission factors vary considerably with the type of control employed, as well as with process conditions. For comparison purposes, the Environmental Protection Agency (EPA) standard for both new and modified plants is 3.0 pounds per ton of 100 percent acid produced (1.5 kilograms per metric ton), maximum 2-hour average, expressed as NO_2.[4] Unless specifically indicated as 100 percent acid, production rates are generally given in terms of the total weight of product (water and acid). For example, a plant producing 500 tons (454 MT) per day of 55 weight percent nitric acid is really producing only 275 tons (250 MT) per day of 100 percent acid.

References for Section 5.9

1. Control of Air Pollution from Nitric Acid Plants. Unpublished Report. Environmental Protection Agency, Research Triangle Park, N.C.

2. Atmospheric Emissions from Nitric Acid Manufacturing Processes. U.S. DHEW, PHS, Division of Air Pollution. Cincinnati, Ohio. Publication Number 999-AP-27. 1966.

3. Unpublished emission data from a nitric acid plant. U.S. DHEW, PHS, EHS, National Air Pollution Control Administration, Office of Criteria and Standards. Durham, N.C. June 1970.

4. Standards of Performance for New Stationary Sources. Environmental Protection Agency, Washington, D.C. Federal Register. *36*(247): December 23, 1971.

5.10 PAINT AND VARNISH

5.10.1 Paint Manufacturing[1]

The manufacture of paint involves the dispersion of a colored oil or pigment in a vehicle, usually an oil or resin, followed by the addition of an organic solvent for viscosity adjustment. Only the physical processes of weighing, mixing, grinding, tinting, thinning, and packaging take place; no chemical reactions are involved.

These processes take place in large mixing tanks at approximately room temperature.

The primary factors affecting emissions from paint manufacture are care in handling dry pigments, types of solvents used, and mixing temperature.[2,3] About 1 or 2 percent of the solvents is lost even under well-controlled conditions. Particulate emissions amount to 0.5 to 1.0 percent of the pigment handled.[4]

5.10.2 Varnish Manufacturing[1-3]

The manufacture of varnish also involves the mixing and blending of various ingredients to produce a wide range of products. However, in this case chemical reactions are initiated by heating. Varnish is cooked in either open or enclosed gas-fired kettles for periods of 4 to 16 hours at temperatures of 200 to 650°F (93 to 340°C).

Varnish cooking emissions, largely in the form or organic compounds, depend on the cooking temperatures and times, the solvent used, the degree of tank enclosure, and the type of air pollution controls used. Emissions from varnish cooking range from 1 to 6 percent of the raw material.

To reduce hydrocarbons from the manufacture of paint and varnish, control techniques include condensers and/or adsorbers on solvent-handling operations, and scrubbers and afterburners on cooking operations. Emission factors for paint and varnish are shown in Table 5.10-1.

Table 5.10-1. EMISSION FACTORS FOR PAINT AND VARNISH MANUFACTURING WITHOUT CONTROL EQUIPMENT[a,b] EMISSION FACTOR RATING: C

Type of product	Particulate		Hydrocarbons[c]	
	lb/ton pigment	kg/MT pigment	lb/ton of product	kg/MT pigment
Paint	2	1	30	15
Varnish				
Bodying oil	–	–	40	20
Oleoresinous	–	–	150	75
Alkyd	–	–	160	80
Acrylic	–	–	20	10

[a] References 2 and 4 through 8.

[b] Afterburners can reduce gaseous hydrocarbon emissions by 99 percent and particulates by about 90 percent. A water spray and oil filter system can reduce particulates by about 90 percent.[5]

[c] Expressed as undefined organic compounds whose composition depends upon the type of varnish or paint.

References for Section 5.10

1. Air Pollutant Emission Factors. Final Report. Resources Research, Inc. Reston, Va. Prepared for National Air Pollution Control Administration, Durham, N.C., under Contract Number CPA-22-69-119. April 1970.

2. Stenburg, R.L. Atmospheric Emissions from Paint and Varnish Operations. Paint Varn. Prod. p. 61-65 and 111-114, September 1959.

3. Private Communication between Resources Research, Incorporated, and National Paint, Varnish and Lacquer Association. September 1969.

4. Unpublished engineering estimates based on plant visits in Washington, D.C. Resources Research, Incorporated. Reston, Va. October 1969.

5. Chatfield, H.E. Varnish Cookers. In: Air Pollution Engineering Manual. Danielson, J. A. (ed.). U.S. DHEW, PHS, National Center for Air Pollution Control. Cincinnati, Ohio. Publication Number 999-AP-40. 1967. p. 688-695.

6. Lunche, E.G. et al. Distribution Survey of Products Emitting Organic Vapors in Los Angeles County. Chem. Eng. Progr. *53*. August 1957.

7. Communication on emissions from paint and varnish operations with G. Sallee, Midwest Research Institute. December 17, 1969.

8. Communication with Roger Higgins, Benjamin Moore Paint Company. June 25, 1968 .

5.11 PHOSPHORIC ACID

Phosphoric acid is produced by two principal methods, the wet process and the thermal process. The wet process is usually employed when the acid is to be used for fertilizer production. Thermal-process acid is normally of higher purity and is used in the manufacture of high-grade chemical and food products.

5.11.1 Wet Process[1,2]

In the wet process, finely ground phosphate rock is fed into a reactor with sulfuric acid to form phosphoric acid and gypsum. There is usually little market for the gypsum produced, and it is handled as waste material in gypsum ponds. The phosphoric acid is separated from the gypsum and other insolubles by vacuum filtration. The acid is then normally concentrated to about 50 to 55 percent P_2O_5. When superphosphoric acid is made, the acid is concentrated to between 70 and 85 percent P_2O_5.

Emissions of gaseous fluorides, consisting mostly of silicon tetrafluoride and hydrogen fluoride, are the major problems from wet-process acid. Table 5.11-1 summarizes the emission factors from both wet-process acid and thermal-process acid.

5.11.2 Thermal Process[1]

In the thermal process, phosphate rock, siliceous flux, and coke are heated in an electric furnace to produce elemental phosphorus. The gases containing the phosphorus vapors are passed through an electrical precipitator to remove entrained dust. In the "one-step" version of the process, the gases are next mixed with air to form P_2O_5 before passing to a water scrubber to form phosphoric acid. In the "two-step" version of the process, the phosphorus is condensed and pumped to a tower in which it is burned with air, and the P_2O_5 formed is hydrated by a water spray in the lower portion of the tower.

The principal emission from thermal-process acid is P_2O_5 acid mist from the absorber tail gas. Since all plants are equipped with some type of acid-mist collection system, the emission factors presented in Table 5.11-1 are based on the listed types of control.

Table 5.11-1. EMISSION FACTORS FOR PHOSPHORIC ACID PRODUCTION
EMISSION FACTOR RATING: B

Source	Particulates		Fluorides	
	lb/ton	kg/MT	lb/ton	kg/MT
Wet process (phosphate rock)				
Reactor, uncontrolled	–	–	18[a]	9[a]
Gypsum pond	–	–	1[b]	1.1[b]
Condenser, uncontrolled	–	–	20[a]	10[a]
Thermal process (phosphorus burned[c])				
Packed tower	4.6	2.3	–	–
Venturi scrubber	5.6	2.8	–	–
Glass-fiber mist eliminator	3.0	1.5	–	–
Wire-mesh mist eliminator	2.7	1.35	–	–
High-pressure-drop mist eliminator	0.2	0.1	–	–
Electrostatic precipitator	1.8	0.9	–	–

[a] References 2 and 3.

[b] Pounds per acre per day (kg/hectare-day); approximately 0.5 acre (0.213 hectare) is required to produce 1 ton of P_2O_5 daily.

[c] Reference 4.

References for Section 5.11

1. Duprey, R.L. Compilation of Air Pollutant Emission Factors. U.S. DHEW, PHS, National Center for Air Pollution Control. Durham, N.C. PHS Publication Number 999-AP-42. 1968. p. 16.

2. Atmospheric Emissions from Wet-Process Phosphoric Acid Manufacture. U.S. DHEW, PHS, EHS, National Air Pollution Control Administration. Raleigh, N.C. Publication Number AP-57. April 1970.

3. Control Techniques for Fluoride Emissions. Internal document. U.S. EPA, Office of Air Programs. Research Triangle Park, N.C. 1970.

4. Atmospheric Emissions from Thermal-Process Phosphoric Acid Manufacturing. Cooperative Study Project: Manufacturing Chemists' Association, Incorporated, and Public Health Service. U.S. DHEW, PHS, National Air Pollution Control Administration. Durham, N.C. Publication Number AP-48. October 1968.

5.12 PHTHALIC ANHYDRIDE

by Pam Canova

5.12.1 General[1]

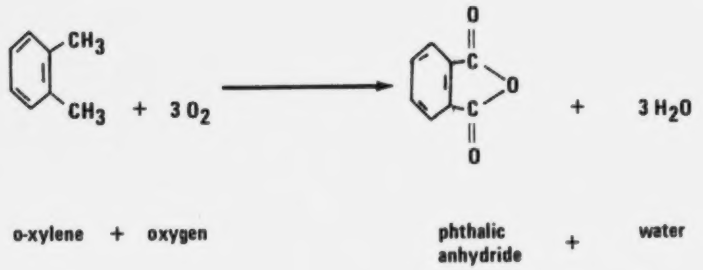
Phthalic anhydride (PAN) production in the United States in 1972 was 0.9 billion pounds per year; this total is estimated to increase to 2.2 billion pounds per year by 1985. Of the current production, 50 percent is used for plasticizers, 25 percent for alkyd resins, 20 percent for unsaturated polyester resins, and 5 percent for miscellaneous and exports. PAN is produced by catalytic oxidation of either ortho-xylene or naphthalene. Since naphthalene is a higher priced feedstock and has a lower feed utilization (about 1.0 lb PAN/lb o-xylene versus 0.97 lb PAN/lb naphthalene), future production growth is predicted to utilize o-xylene. Because emission factors are intended for future as well as present application, this report will focus mainly on PAN production utilizing o-xylene as the main feedstock.

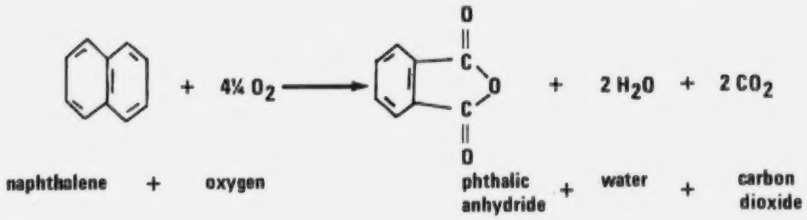
The processes for producing PAN by o-xylene or naphthalene are the same except for reactors, catalyst handling, and recovery facilities required for fluid bed reactors.

In PAN production using o-xylene as the basic feedstock, filtered air is preheated, compressed, and mixed with vaporized o-xylene and fed into the fixed-bed tubular reactors. The reactors contain the catalyst, vanadium pentoxide, and are operated at 650 to 725°F (340 to 385°C). Small amounts of sulfur dioxide are added to the reactor feed to maintain catalyst activity. Exothermic heat is removed by a molten salt bath circulated around the reactor tubes and transferred to a steam generation system.

Naphthalene-based feedstock is made up of vaporized naphthalene and compressed air. It is transferred to the fluidized bed reactor and oxidized in the presence of a catalyst, vanadium pentoxide, at 650 to 725°F (340 to 385°C). Cooling tubes located in the catalyst bed remove the exothermic heat which is used to produce high-pressure steam. The reactor effluent consists of PAN vapors, entrained catalyst, and various by-products and non-reactant gas. The catalyst is removed by filtering and returned to the reactor.

The chemical reactions for air oxidation of o-xylene and naphthalene are as follows.





The reactor effluent containing crude PAN plus products from side reactions and excess oxygen passes to a series of switch condensers where the crude PAN cools and crystallizes. The condensers are alternately cooled and then heated, allowing PAN crystals to form and then melt from the condenser tube fins.

The crude liquid is transferred to a pretreatment section in which phthalic acid is dehydrated to anhydride. Water, maleic anhydride, and benzoic acid are partially evaporated. The liquid then goes to a vacuum distillation section where pure PAN (99.8 wt. percent pure) is recovered. The product can be stored and shipped either as a liquid or a solid (in which case it is dried, flaked, and packaged in multi-wall paper bags). Tanks for holding liquid PAN are kept at 300°F (150°C) and blanketed with dry nitrogen to prevent the entry of oxygen (fire) or water vapor (hydrolysis to phthalic acid).

Maleic anhydride is currently the only by-product being recovered.

Figures 1 and 2 show the process flow for air oxidation of o-xylene and naphthalene, respectively.

5.12.2 Emissions and Controls[1]

Emissions from o-xylene and naphthalene storage are small and presently are not controlled.

The major contributor of emissions is the reactor and condenser effluent which is vented from the condenser unit. Particulate, sulfur oxides (for o-xylene-based production), and carbon monoxide make up the emissions, with carbon monoxide comprising over half the total. The most efficient (96 percent) system of control is the combined usage of a water scrubber and thermal incinerator. A thermal incinerator alone is approximately 95 percent efficient in combustion of pollutants for o-xylene-based production, and 80 percent efficient for naphthalene-based production. Thermal incinerators with steam generation show the same efficiencies as thermal incinerators alone. Scrubbers have a 99 percent efficiency in collecting particulates, but are practically ineffective in reducing carbon monoxide emissions. In naphthalene-based production, cyclones can be used to control catalyst dust emissions with 90 to 98 percent efficiency.

Pretreatment and distillation emissions—particulates and hydrocarbons—are normally processed through the water scrubber and/or incinerator used for the main process stream (reactor and condenser) or scrubbers alone, with the same efficiency percentages applying.

Product storage in the liquid phase results in small amounts of gaseous emissions. These gas streams can either be sent to the main process vent gas control devices or first processed through sublimation boxes or devices used to recover escaped PAN. Flaking and bagging emissions are negligible, but can be sent to a cyclone for recovery of PAN dust. Exhaust from the cyclone presents no problem.

Table 5.12-1 gives emission factors for controlled and uncontrolled emissions from the production of PAN.

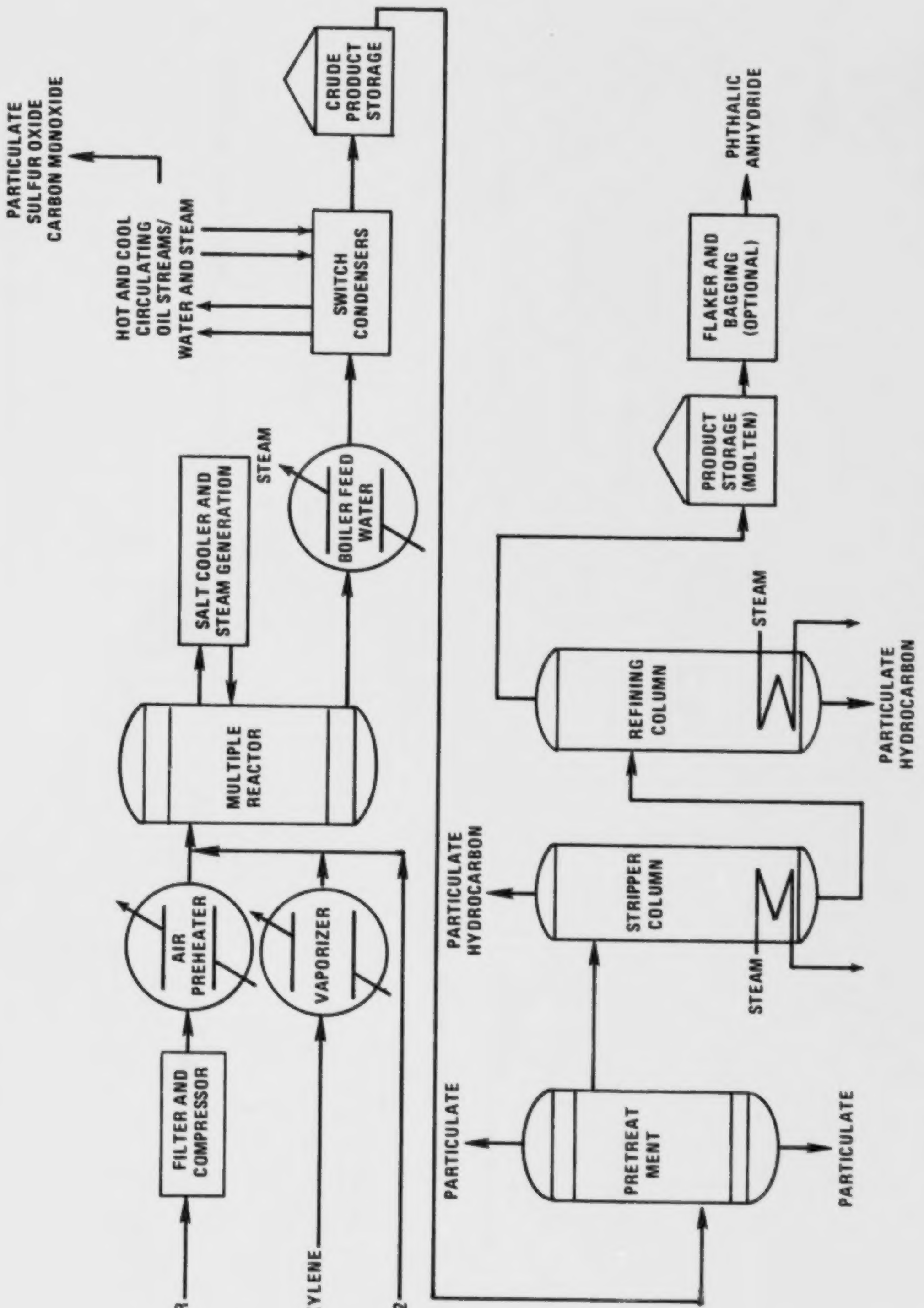

AIR
FILTER AND COMPRESSOR
AIR PREHEATER
o-XYLENE
VAPORIZER
SO_2
MULTIPLE REACTOR
SALT COOLER AND STEAM GENERATION
BOILER FEED WATER
STEAM
SWITCH CONDENSERS
HOT AND COOL CIRCULATING OIL STREAMS/ WATER AND STEAM
PARTICULATE SULFUR OXIDE CARBON MONOXIDE
CRUDE PRODUCT STORAGE
PARTICULATE
PRETREAT MENT
PARTICULATE
PARTICULATE HYDROCARBON
STRIPPER COLUMN
STEAM
REFINING COLUMN
STEAM
PARTICULATE HYDROCARBON
PRODUCT STORAGE (MOLTEN)
FLAKER AND BAGGING (OPTIONAL)
PHTHALIC ANHYDRIDE

Figure 5.12-1. Flow diagram for phthalic anhydride using o-xylene as basic feedstock.[1]

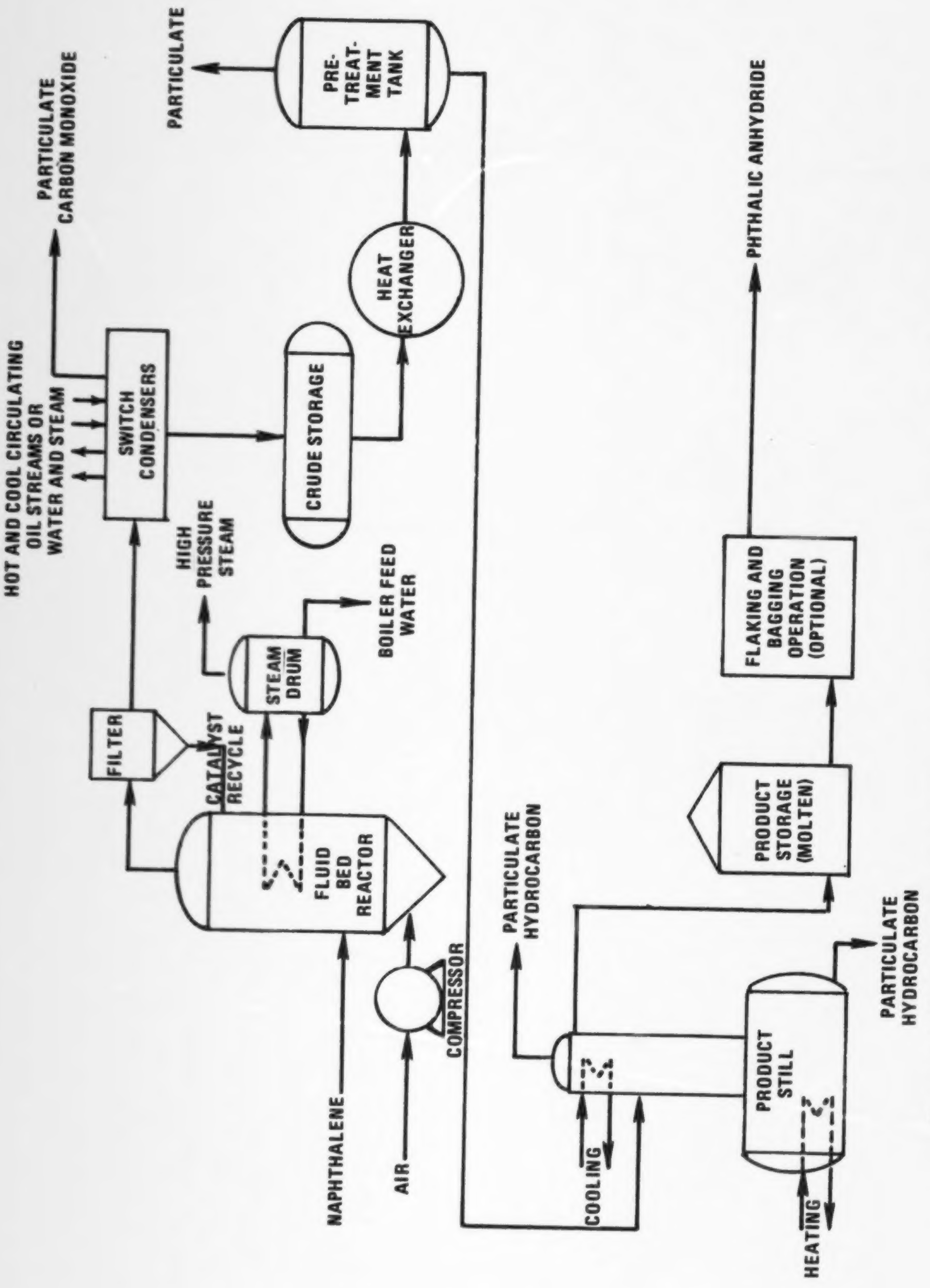

NAPHTHALENE
AIR
COMPRESSOR
FLUID BED REACTOR
FILTER
CATALYST RECYCLE
STEAM DRUM
HIGH PRESSURE STEAM
BOILER FEED WATER
HOT AND COOL CIRCULATING OIL STREAMS OR WATER AND STEAM
SWITCH CONDENSERS
PARTICULATE CARBON MONOXIDE
CRUDE STORAGE
HEAT EXCHANGER
PRE-TREAT-MENT TANK
PARTICULATE
COOLING
HEATING
PARTICULATE HYDROCARBON
PRODUCT STILL
PARTICULATE HYDROCARBON
PRODUCT STORAGE (MOLTEN)
FLAKING AND BAGGING OPERATION (OPTIONAL)
PHTHALIC ANHYDRIDE

Figure 5.12-2. Flow diagram for phthalic anhydride using naphthalene as basic feedstock.1

Table 5.12-1. EMISSION FACTORS FOR PHTHALIC ANHYDRIDE[1,a]
EMISSION FACTOR RATING: B

Process	Particulate		SO_x		HC		CO	
	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT
Oxidation of o-xylene[b]								
Main process stream[c]								
Uncontrolled	138[d]	69[d]	9.4[e]	4.7[e]	0	0	301	151
W/scrubber and thermal incinerator	6	3	9.4	4.7	0	0	12	6
W/thermal incinerator	7	4	9.4	4.7	0	0	15	8
W/incinerator with steam generator	7	4	9.4	4.7	0	0	15	8
Pretreatment								
Uncontrolled	13[f]	6.4[f]	0	0	0	0	0	0
W/scrubber and thermal incinerator	0.5	0.3	0	0	0	0	0	0
W/thermal incinerator	0.7	0.4	0	0	0	0	0	0
Distillation								
Uncontrolled	89[d]	45[d]	0	0	2.4	1.2	0	0
W/scrubber and thermal incinerator	4	2	0	0	<0.1	<0.1	0	0
W/thermal incinerator	4	2	0	0	0.1	<0.1	0	0
Oxidation of naphthalene[b]								
Main process stream[c]								
Uncontrolled	56[g,i]	28[g,i]	0	0	0	0	100	50
W/thermal incinerator	11	6	0	0	0	0	20	10
W/scrubber	0.6	0.3	0	0	0	0	100	50
Pretreatment								
Uncontrolled	5[h]	2.5[h]	0	0	0	0	0	0
W/thermal incinerator	1	0.5	0	0	0	0	0	0
W/scrubber	<0.1	<0.1	0	0	0	0	0	0
Distillation								
Uncontrolled	38[g]	19[g]	0	0	10	5	0	0
W/thermal incinerator	8	4	0	0	2	1	0	0
W/scrubber	0.4	0.2	0	0	0.1	<0.1	0	0

[a] Emission factors are in units of pounds of pollutant per ton (kilogram of pollutant per metric ton) of phthalic anhydride produced.

[b] Control devices listed are those currently being used by phthalic anhydride plants.

[c] Main process stream includes the reactor and multiple switch condensers as vented through the condenser unit.

[d] Particulate consists of phthalic anhydride, maleic anhydride, and benzoic acid.

[e] Emissions change with catalyst age. Value shown corresponds to relatively fresh catalyst. Can be 19 to 25 lb/ton (9.5 to 13 kg/MT) for aged catalyst.

[f] Particulate consists of phthalic anhydride and maleic anhydride.

[g] Particulate consists of phthalic anhydride, maleic anhydride, and naphthaquinone.

[h] Particulate is phthalic anhydride.

[i] Particulate does not include catalyst dust which is controlled by cyclones with an efficiency of 90 to 98 percent.

Reference for Section 5.12

1. Engineering and Cost Study of Air Pollution Control for the Petrochemical Industry. Vol 7: Phthalic Anhydride Manufacture from Ortho-Xylene. Houdry Division, Air Products and Chemicals, Inc., Marcus Hook, Pa. Prepared for Environmental Protection Agency, Research Triangle Park, N.C. Publication No. EPA-450/3-73-006-g. July 1975.

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5.13 PLASTICS

5.13.1 Process Description[1]

The manufacture of most resins or plastics begins with the polymerization or linking of the basic compound (monomer), usually a gas or liquid, into high molecular weight noncrystalline solids. The manufacture of the basic monomer is not considered part of the plastics industry and is usually accomplished at a chemical or petroleum plant.

The manufacture of most plastics involves an enclosed reaction or polymerization step, a drying step, and a final treating and forming step. These plastics are polymerized or otherwise combined in completely enclosed stainless steel or glass-lined vessels. Treatment of the resin after polmerization varies with the proposed use. Resins for moldings are dried and crushed or ground into molding powder. Resins such as the alkyd resins that are to be used for protective coatings are normally transferred to an agitated thinning tank, where they are thinned with some type of solvent and then stored in large steel tanks equipped with water-cooled condensers to prevent loss of solvent to the atmosphere. Still other resins are stored in latex form as they come from the kettle.

5.13.2 Emissions and Controls[1]

The major sources of air contamination in plastics manufacturing are the emissions of raw materials or monomers, emissions of solvents or other volatile liquids during the reaction, emissions of sublimed solids such as phthalic anhydride in alkyd production, and emissions of solvents during storage and handling of thinned resins. Emission factors for the manufacture of plastics are shown in Table 5.13-1.

Table 5.13-1. EMISSION FACTORS FOR PLASTICS MANUFACTURING WITHOUT CONTROLS[a]
EMISSION FACTOR RATING: E

Type of plastic	Particulate		Gases	
	lb/ton	kg/MT	lb/ton	kg/MT
Polyvinyl chloride	35[b]	17.5[b]	17[c]	8.5[c]
Polypropylene	3	1.5	0.7[d]	0.35[d]
General	5 to 10	2.5 to 5	–	–

[a] References 2 and 3.
[b] Usually controlled with a fabric filter efficiency of 98 to 99 percent.
[c] As vinyl chloride.
[d] As propylene.

Much of the control equipment used in this industry is a basic part of the system and serves to recover a reactant or product. These controls include floating roof tanks or vapor recovery systems on volatile material, storage units, vapor recovery systems (adsorption or condensers), purge lines that vent to a flare system, and recovery systems on vacuum exhaust lines.

References for Section 5.13

1. Air Pollutant Emission Factors. Final Report. Resources Research, Inc. Reston, Va. Prepared for National Air Pollution Control Administration, Durham, N.C., under Contract Number CPA-22-69-119. April 1970.

2. Unpublished data from industrial questionnaire. U.S. DHEW, PHS, National Air Pollution Control Administration, Division of Air Quality and Emissions Data. Durham, N.C. 1969.

3. Private Communication between Resources Research, Incorporated, and Maryland State Department of Health, Baltimore, Md. November 1969.

5.14 PRINTING INK

5.14.1 Process Description[1]

There are four major classes of printing ink: letterpress and lithographic inks, commonly called oil or paste inks; and flexographic and rotogravure inks, which are referred to as solvent inks. These inks vary considerably in physical appearance, composition, method of application, and drying mechanism. Flexographic and rotogravure inks have many elements in common with the paste inks but differ in that they are of very low viscosity, and they almost always dry by evaporation of highly volatile solvents.[2]

There are three general processes in the manufacture of printing inks: (1) cooking the vehicle and adding dyes, (2) grinding of a pigment into the vehicle using a roller mill, and (3) replacing water in the wet pigment pulp by an ink vehicle (commonly known as the flushing process).[3] The ink "varnish" or vehicle is generally cooked in large kettles at 200° to 600°F (93° to 315°C) for an average of 8 to 12 hours in much the same way that regular varnish is made. Mixing of the pigment and vehicle is done in dough mixers or in large agitated tanks. Grinding is most often carried out in three-roller or five-roller horizontal or vertical mills.

5.14.2 Emissions and Controls[1,4]

Varnish or vehicle preparation by heating is by far the largest source of ink manufacturing emissions. Cooling the varnish components – resins, drying oils, petroleum oils, and solvents – produces odorous emissions. At about 350°F (175°C) the products begin to decompose, resulting in the emission of decomposition products from the cooking vessel. Emissions continue throughout the cooking process with the maximum rate of emissions occuring just after the maximum temperature has been reached. Emissions from the cooking phase can be reduced by more than 90 percent with the use of scrubbers or condensers followed by afterburners.[4,5]

Compounds emitted from the cooking of oleoresinous varnish (resin plus varnish) include water vapor, fatty acids, glycerine, acrolein, phenols, aldehydes, ketones, terpene oils, terpenes, and carbon dioxide. Emissions of thinning solvents used in flexographic and rotogravure inks may also occur.

The quantity, composition, and rate of emissions from ink manufacturing depend upon the cooking temperature and time, the ingredients, the method of introducing additives, the degree of stirring, and the extent of air or inert gas blowing. Particulate emissions resulting from the addition of pigments to the vehicle are affected by the type of pigment and its particle size. Emission factors for the manufacture of printing ink are presented in Table 5.14-1.

Table 5.14-1. EMISSION FACTORS FOR PRINTING INK MANUFACTURING[a]
EMISSION FACTOR RATING: E

Type of process	Gaseous organic[b]		Particulates	
	lb/ton of product	kg/MT of product	lb/ton of pigment	kg/MT of pigment
Vehicle cooking				
General	120	60	–	–
Oils	40	20	–	–
Oleoresinous	150	75	–	–
Alkyds	160	80	–	–
Pigment mixing	–	–	2	1

[a] Based on data from section on paint and varnish.
[b] Emitted as gas, but rapidly condense as the effluent is cooled.

References for Section 5.14

1. Air Pollutant Emission Factors. Final Report. Resources Research Inc. Reston, Va. Prepared for National Air Pollution Control Administration, Durham, N.C., under Contract Number CPA-22-69-119. April 1970.

2. Shreve, R. N. Chemical Process Industries, 3rd Ed. New York, McGraw Hill Book Co. 1967. p. 454-455.

3. Larsen, L.M. Industrial Printing Inks. New York, Reinhold Publishing Company. 1962.

4. Chatfield, H.E. Varnish Cookers. In: Air Pollution Engineering Manual. Danielson, J.A. (ed.). U.S. DHEW, PHS, National Center for Air Pollution Control. Cincinnati, Ohio. Publication Number 999-AP-40. 1967. p. 688-695.

5. Private communication with Interchemical Corporation, Ink Division. Cincinnati, Ohio. November 10, 1969.

5.15 SOAP AND DETERGENTS

5.15.1 Soap Manufacture[1]

The manufacture of soap entails the catalytic hydrolysis of various fatty acids with sodium or potassium hydroxide to form a glycerol-soap mixture. This mixture is separated by distillation, then neutralized and blended to produce soap. The main atmospheric pollution problem in the manufacture of soap is odor, and, if a spray drier is used, a particulate emission problem may also occur. Vent lines, vacuum exhausts, product and raw material storage, and waste streams are all potential odor sources. Control of these odors may be achieved by scrubbing all exhaust fumes and, if necessary, incinerating the remaining compounds. Odors emanating from the spray drier may be controlled by scrubbing with an acid solution.

5.15.2 Detergent Manufacture[1]

The manufacture of detergents generally begins with the sulfuration by sulfuric acid of a fatty alcohol or linear alkylate. The sulfurated compound is then neutralized with caustic solution (NaOH), and various dyes, perfumes, and other compounds are added.[2,3] The resulting paste or slurry is then sprayed under pressure into a vertical drying tower where it is dried with a stream of hot air (400° to 500°F or 204° to 260°C). The dried detergent is then cooled and packaged. The main source of particulate emissions is the spray-drying tower. Odors may also be emitted from the spray-drying operation and from storage and mixing tanks. Particulate emissions from spray-drying operations are shown in Table 5.15-1.

Table 5.15-1. PARTICULATE EMISSION FACTORS FOR SPRAY-DRYING DETERGENTS[a]
EMISSION FACTOR RATING: B

Control device	Overall efficiency, %	Particulate emissions	
		lb/ton of product	kg/MT of product
Uncontrolled	–	90	45
Cyclone[b]	85	14	7
Cyclone followed by:			
Spray chamber	92	7	3.5
Packed scrubber	95	5	2.5
Venturi scrubber	97	3	1.5

[a] Based on analysis of data in References 2 through 6.

[b] Some type of primary collector, such as a cyclone, is considered an integral part of the spray-drying system.

References for Section 5.15

1. Air Pollutant Emission Factors. Final Report. Resources Research Inc. Reston, Va. Prepared for National Air Pollution Control Administration, Durham, N.C., under Contract Number CPA-22-69-119. April 1970.

2. Phelps, A.H. Air Pollution Aspects of Soap and Detergent Manufacture. J. Air Pol. Control Assoc. *17*(8):505-507, August 1967.

3. Shreve, R.N. Chemical Process Industries. 3rd Ed. New York, McGraw-Hill Book Company. 1967. p. 544-563.

4. Larsen, G.P., G.I. Fischer, and W.J. Hamming. Evaluating Sources of Air Pollution. Ind. Eng. Chem. *45*:1070-1074, May 1953.

5. McCormick, P.Y., R.L. Lucas, and D.R. Wells. Gas-Solid Systems. In: Chemical Engineer's Handbook. Perry, J.H. (ed.). New York, McGraw-Hill Book Company. 1963. p. 59.

6. Private communication with Maryland State Department of Health, Baltimore, Md. November 1969.

5.16 SODIUM CARBONATE (Soda Ash)

5.16.1 Process Description[1]

Soda ash is manufactured by three processes: (1) the natural or Lake Brine process, (2) the Solvay process (ammonia-soda), and (3) the electrolytic soda-ash process. Because the Solvay process accounts for over 80 percent of the total production of soda ash, it will be the only one discussed in this section.

In the Solvay process, the basic raw materials are ammonia, coke, limestone (calcium carbonate), and salt (sodium chloride). The salt, usually in the unpurified form of a brine, is first purified in a series of absorbers by precipitation of the heavy metal ions with ammonia and carbon dioxide. In this process sodium bicarbonate is formed. This bicarbonate coke is heated in a rotary kiln, and the resultant soda ash is cooled and conveyed to storage.

5.16.2 Emissions

The major source of emissions from the manufacture of soda ash is the release of ammonia. Small amounts of ammonia are emitted in the gases vented from the brine purification system. Intermittent losses of ammonia can also occur during the unloading of tank trucks into storage tanks. The major sources of dust emissions include rotary dryers, dry solids handling, and processing of lime. Dust emissions of fine soda ash also occur from conveyor transfer points and air classification systems, as well as during tank-car loading and packaging. Emission factors are summarized in Table 5.16-1.

Table 5.16-1. EMISSION FACTORS FOR SODA-ASH PLANTS WITHOUT CONTROLS
EMISSION FACTOR RATING: D

Type of source	Particulates		Ammonia	
	lb/ton	kg/MT	lb/ton	kg/MT
Ammonia recovery[a,b]	–	–	7	3.5
Conveying, transferring, loading, etc.[c]	6	3	–	–

[a] Reference 2.
[b] Represents ammonia loss following the recovery system.
[c] Based on data in References 3 through 5.

References for Section 5.16

1. Air Pollutant Emission Factors. Final Report. Resources Research, Inc. Reston, Va. Prepared for National Air Pollution Control Administration, Durham, N.C., under Contract Number CPA-22-69-119. April 1970.

2. Shreve, R.N. Chemical Process Industries, 3rd Ed. New York, McGraw-Hill Book Company. 1967. p. 225-230.

3. Facts and Figures for the Chemical Process Industries. Chem. Eng. News. *43*:51-118, September 6, 1965.

4. Faith, W.L., D.B. Keyes, and R.L. Clark. Industrial Chemicals, 3rd Ed. New York, John Wiley and Sons, Inc. 1965.

5. Kaylor, F.B. Air Pollution Abatement Program of a Chemical Processing Industry. J. Air Pol. Control Assoc. *15*:65-67, February 1965.

5.17 SULFURIC ACID

Revised by William Vatavuk
and Donald Carey

5.17.1 Process Description

All sulfuric acid is made by either the lead chamber or the contact process. Because the contact process accounts for more than 97 percent of the total sulfuric acid production in the United States, it is the only process discussed in this section. Contact plants are generally classified according to the raw materials charged to them: (1) elemental sulfur burning, (2) spent acid and hydrogen sulfide burning, and (3) sulfide ores and smelter gas burning plants. The relative contributions from each type of plant to the total acid production are 68, 18.5, and 13.5 percent, respectively.

All contact processes incorporate three basic operations, each of which corresponds to a distinct chemical reaction. First, the sulfur in the feedstock is burned to sulfur dioxide:

$$\underset{\text{Sulfur}}{S} + \underset{\text{Oxygen}}{O_2} \rightarrow \underset{\substack{\text{Sulfur}\\\text{dioxide}}}{SO_2}. \tag{1}$$

Then, the sulfur dioxide is catalytically oxidized to sulfur trioxide:

$$\underset{\substack{\text{Sulfur}\\\text{dioxide}}}{2SO_2} + \underset{\text{Oxygen}}{O_2} \rightarrow \underset{\substack{\text{Sulfur}\\\text{trioxide}}}{2SO_3}. \tag{2}$$

Finally, the sulfur trioxide is absorbed in a strong, aqueous solution of sulfuric acid:

$$\underset{\substack{\text{Sulfur}\\\text{trioxide}}}{SO_3} + \underset{\text{Water}}{H_2O} \rightarrow \underset{\substack{\text{Sulfuric}\\\text{acid}}}{H_2SO_4}. \tag{3}$$

5.17.1.1 Elemental Sulfur-Burning Plants[1,2] - Elemental sulfur, such as Frasch-process sulfur from oil refineries, is melted, settled, or filtered to remove ash and is fed into a combustion chamber. The sulfur is burned in clean air that has been dried by scrubbing with 93 to 99 percent sulfuric acid. The gases from the combustion chamber are cooled and then enter the solid catalyst (vanadium pentoxide) converter. Usually, 95 to 98 percent of the sulfur dioxide from the combustion chamber is converted to sulfur trioxide, with an accompanying large evolution of heat. After being cooled, the converter exit gas enters an absorption tower where the sulfur trioxide is absorbed with 98 to 99 percent sulfuric acid. The sulfur trioxide combines with the water in the acid and forms more sulfuric acid.

If oleum, a solution of uncombined SO_3 in H_2SO_4, is produced, SO_3 from the converter is first passed to an oleum tower that is fed with 98 percent acid from the absorption system. The gases from the oleum tower are then pumped to the absorption column where the residual sulfur trioxide is removed.

A schematic diagram of a contact process sulfuric acid plant that burns elemental sulfur is shown in Figure 5.17-1.

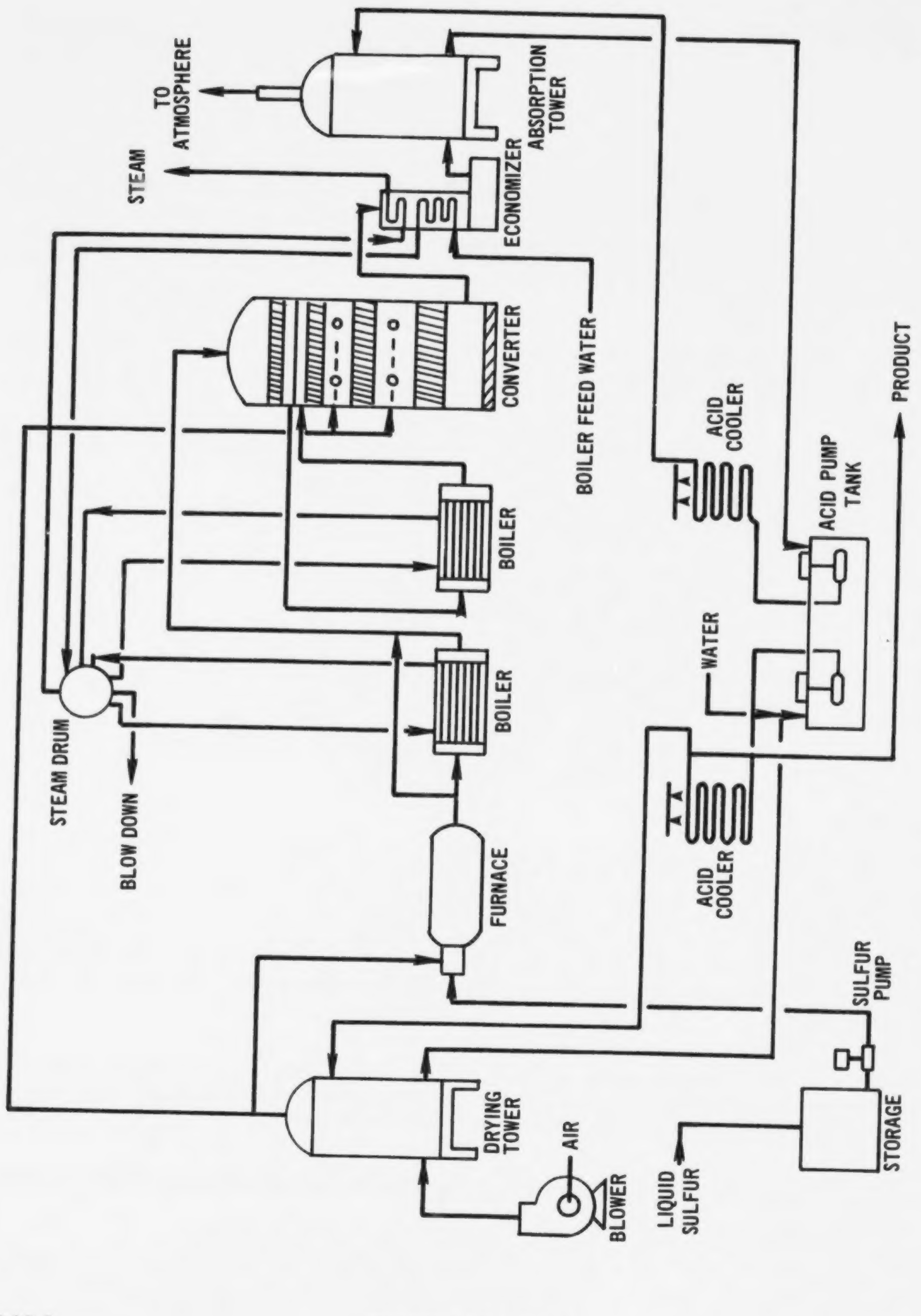
TO ATMOSPHERE
STEAM
ABSORPTION TOWER
ECONOMIZER
CONVERTER
BOILER FEED WATER
BOILER
BOILER
STEAM DRUM
BLOW DOWN
FURNACE
DRYING TOWER
AIR
BLOWER
LIQUID SULFUR
STORAGE
SULFUR PUMP
ACID COOLER
WATER
ACID PUMP TANK
ACID COOLER
PRODUCT

Figure 5.17-1. Basic flow diagram of contact-process sulfuric acid plant burning elemental sulfur.

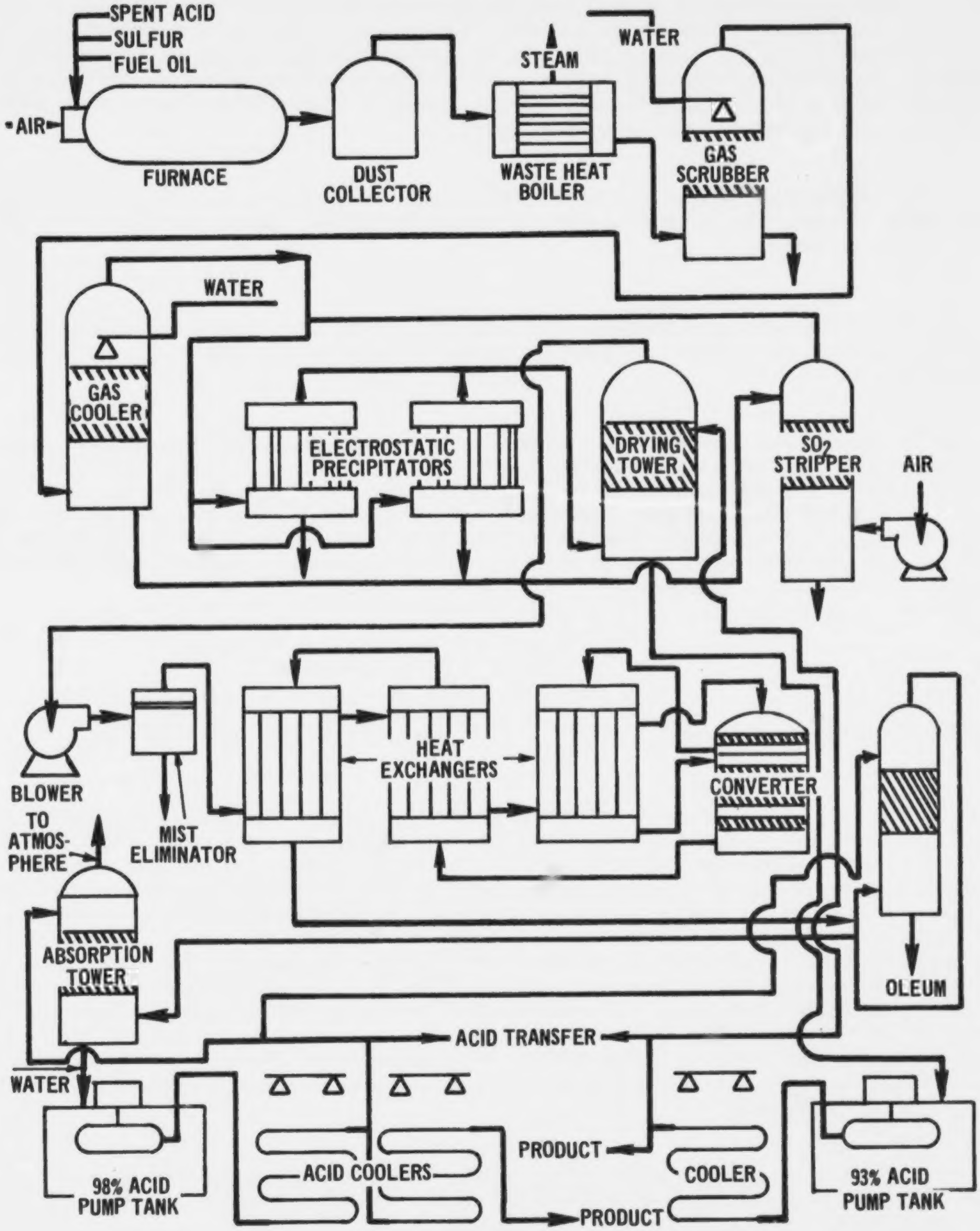
SPENT ACID
SULFUR
FUEL OIL
AIR
FURNACE
DUST COLLECTOR
STEAM
WASTE HEAT BOILER
WATER
GAS SCRUBBER
WATER
GAS COOLER
ELECTROSTATIC PRECIPITATORS
DRYING TOWER
SO_2 STRIPPER
AIR
BLOWER
MIST ELIMINATOR
HEAT EXCHANGERS
CONVERTER
TO ATMOSPHERE
ABSORPTION TOWER
OLEUM
ACID TRANSFER
WATER
PRODUCT
ACID COOLERS
COOLER
PRODUCT
98% ACID PUMP TANK
93% ACID PUMP TANK

Figure 5.17-2. Basic flow diagram of contact-process sulfuric acid plant burning spent acid.

5.17.1.2 Spent Acid and Hydrogen Sulfide Burning Plants[1,2] - Two types of plants are used to process this type of sulfuric acid. In one the sulfur dioxide and other combustion products from the combustion of spent acid and/or hydrogen sulfide with undried atmospheric air are passed through gas-cleaning and mist-removal equipment. The gas stream next passes through a drying tower. A blower draws the gas from the drying tower and discharges the sulfur dioxide gas to the sulfur trioxide converter. A schematic diagram of a contact-process sulfuric acid plant that burns spent acid is shown in Figure 5.17-2.

In a "wet-gas plant," the wet gases from the combustion chamber are charged directly to the converter with no intermediate treatment. The gas from the converter flows to the absorber, through which 93 to 98 percent sulfuric acid is circulating.

5.17.1.3 Sulfide Ores and Smelter Gas Plants - The configuration of this type of plant is essentially the same as that of a spent-acid plant (Figure 5.17-2) with the primary exception that a roaster is used in place of the combustion furnace.

The feed used in these plants is smelter gas, available from such equipment as copper converters, reverberatory furnaces, roasters, and flash smelters. The sulfur dioxide in the gas is contaminated with dust, acid mist, and gaseous impurities. To remove the impurities the gases must be cooled to essentially atmospheric temperature and passed through purification equipment consisting of cyclone dust collectors, electrostatic dust and mist precipitators, and scrubbing and gas-cooling towers. After the gases are cleaned and the excess water vapor is removed, they are scrubbed with 98 percent acid in a drying tower. Beginning with the drying tower stage, these plants are nearly identical to the elemental sulfur plants shown in Figure 5.17-1.

5.17.2 Emissions and Controls

5.17.2.1 Sulfur Dioxide[1-3] - Nearly all sulfur dioxide emissions from sulfuric acid plants are found in the exit gases. Extensive testing has shown that the mass of these SO_2 emissions is an inverse function of the sulfur conversion efficiency (SO_2 oxidized to SO_3). This conversion is, in turn, affected by the number of stages in the catalytic converter, the amount of catalyst used, the temperature and pressure, and the concentrations of the reactants, sulfur dioxide and oxygen. For example, if the inlet SO_2 concentration to the converter were 8 percent by volume (a representative value), and the conversion temperature were 473°C, the conversion efficiency would be 96 percent. At this conversion, the uncontrolled emission factor for SO_2 would be 55 pounds per ton (27.5 kg/MT) of 100 percent sulfuric acid produced, as shown in Table 5.17-1. For purposes of comparison, note that the Environmental Protection Agency performance standard[3] for new and modified plants is 4 pounds per ton (2kg / MT) of 100 percent acid produced, maximum 2-hour average. As Table 5.17-1 and Figure 5.17-3 indicate, achieving this standard requires a conversion efficiency of 99.7 percent in an uncontrolled plant or the equivalent SO_2 collection mechanism in a controlled facility. Most single absorption plants have SO_2 conversion efficiencies ranging from 95 to 98 percent.

In addition to exit gases, small quantities of sulfur oxides are emitted from storage tank vents and tank car and tank truck vents during loading operations; from sulfuric acid concentrators; and through leaks in process equipment. Few data are available on emissions from these sources.

Of the many chemical and physical means for removing SO_2 from gas streams, only the dual absorption and the sodium sulfite-bisulfite scrubbing processes have been found to increase acid production without yielding unwanted by-products.

Table 5.17-1. EMISSION FACTORS FOR SULFURIC ACID PLANTS[a]
EMISSION FACTOR RATING: A

Conversion of SO_2 to SO_3, %	SO_2 emissions	
	lb/ton of 100 % H_2SO_4	kg/MT of 100 % H_2SO_4
93	96	48.0
94	82	41.0
95	70	35.0
96	55	27.5
97	40	20.5
98	27	13.0
99	14	7.0
99.5	7	3.5
99.7	4	2.0
100	0	0.0

[a] Reference 1.

[b] The following linear interpolation formula can be used for calculating emission factors for conversion efficiencies between 93 and 100 percent: emission factor (lb/ton acid) = -13.65 (percent conversion efficiency) + 1365.

In the dual absorption process, the SO_3 gas formed in the primary converter stages is sent to a primary absorption tower where H_2SO_4 is formed. The remaining unconverted sulfur dioxide is forwarded to the final stages in the converter, from whence it is sent to the secondary absorber for final sulfur trioxide removal. The result is the conversion of a much higher fraction of SO_2 to SO_3 (a conversion of 99.7 percent or higher, on the average, which meets the performance standard). Furthermore, dual absorption permits higher converter inlet sulfur dioxide concentrations than are used in single absorption plants because the secondary conversion stages effectively remove any residual sulfur dioxide from the primary absorber.

Where dual absorption reduces sulfur dioxide emissions by increasing the overall conversion efficiency, the sodium sulfite-bisulfite scrubbing process removes sulfur dioxide directly from the absorber exit gases. In one version of this process, the sulfur dioxide in the waste gas is absorbed in a sodium sulfite solution, separated, and recycled to the plant. Test results from a 750 ton (680 MT) per day plant equipped with a sulfite scrubbing system indicated an average emission factor of 2.7 pounds per ton (1.35 kg/MT).

15.17.2.2 Acid Mist[1-3] - Nearly all the acid mist emitted from sulfuric acid manufacturing can be traced to the absorber exit gases. Acid mist is created when sulfur trioxide combines with water vapor at a temperature below the dew point of sulfur trioxide. Once formed within the process system, this mist is so stable that only a small quantity can be removed in the absorber.

In general, the quantity and particle size distribution of acid mist are dependent on the type of sulfur feedstock used, the strength of acid produced, and the conditions in the absorber. Because it contains virtually no water vapor, bright elemental sulfur produces little acid mist when burned; however, the hydrocarbon impurities in other feedstocks – dark sulfur, spent acid, and hydrogen sulfide – oxidize to water vapor during combustion. The water vapor, in turn, combines with sulfur trioxide as the gas cools in the system.

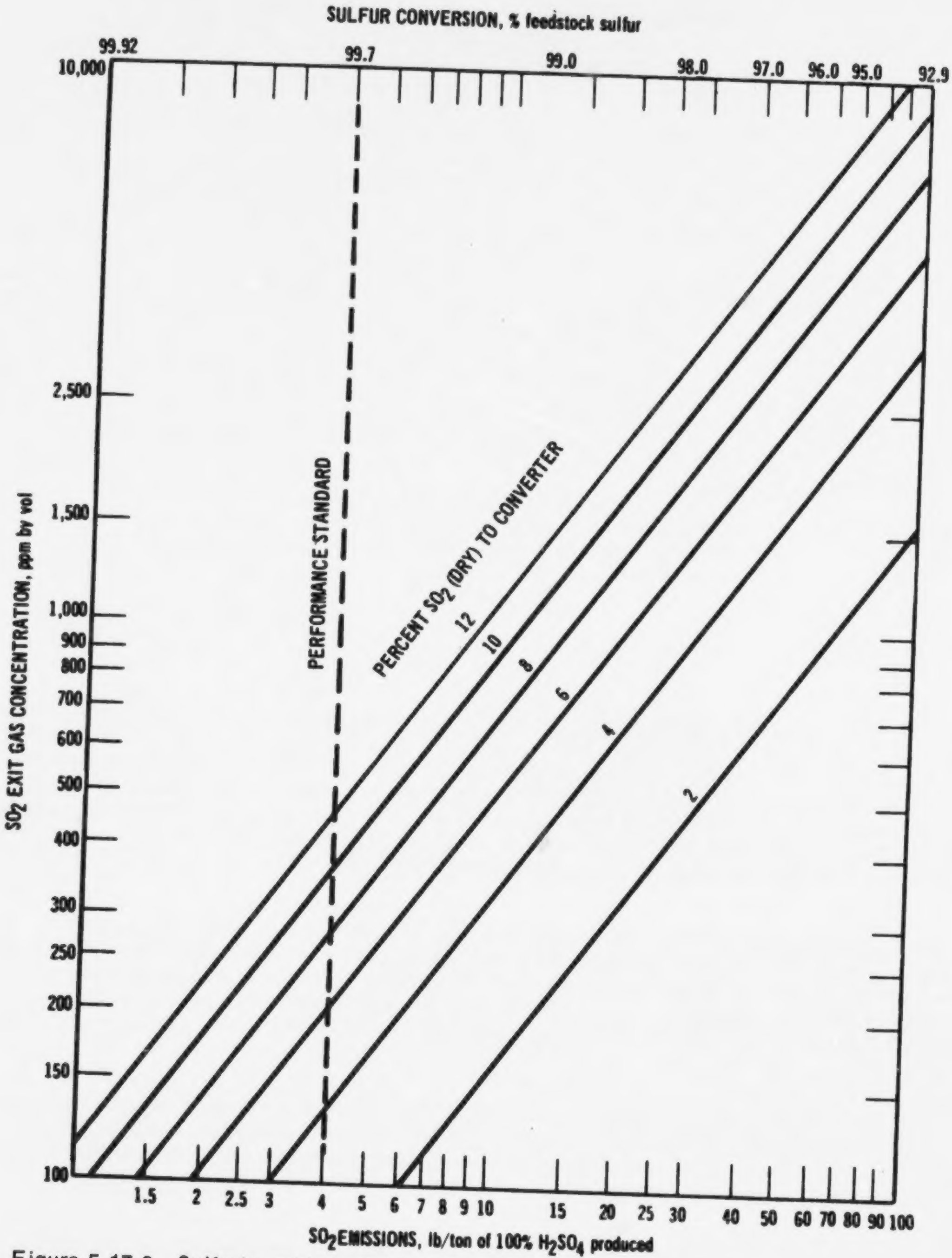

Figure 5.17-3. Sulfuric acid plant feedstock sulfur conversion versus volumetric and mass SO_2 emissions at various inlet SO_2 concentrations by volume.

The strength of acid produced—whether oleum or 99 percent sulfuric acid—also affects mist emissions. Oleum plants produce greater quantities of finer, more stable mist. For example, uncontrolled mist emissions from oleum plants burning spent acid range from 0.1 to 10.0 pounds per ton (0.05 to 5.0 kg/MT), while those from 98 percent acid plants burning elemental sulfur range from 0.4 to 4.0 pounds per ton (0.2 to 2.0 kg/MT). Furthermore, 85 to 95 weight percent of the mist particles from oleum plants are less than 2 microns in diameter, compared with only 30 weight percent that are less than 2 microns in diameter from 98 percent acid plants.

The operating temperature of the absorption column directly affects sulfur trioxide absorption and, accordingly, the quality of acid mist formed after exit gases leave the stack. The optimum absorber operating temperature is dependent on the strength of the acid produced, throughput rates, inlet sulfur trioxide concentrations, and other variables peculiar to each individual plant. Finally, it should be emphasized that the percentage conversion of sulfur dioxide to sulfur trioxide has no direct effect on acid mist emissions. In Table 5.17-2 uncontrolled acid mist emissions are presented for various sulfuric acid plants.

Two basic types of devices, electrostatic precipitators and fiber mist eliminators, effectively reduce the acid mist concentration from contact plants to less than the EPA new-source performance standard, which is 0.15 pound per ton (0.075 kg/MT) of acid. Precipitators, if properly maintained, are effective in collecting the mist particles at efficiencies up to 99 percent (see Table 5.17-3).

The three most commonly used fiber mist eliminators are the vertical tube, vertical panel, and horizontal dual-pad types. They differ from one another in the arrangement of the fiber elements, which are composed of either chemically resistant glass or fluorocarbon, and in the means employed to collect the trapped liquid. The operating characteristics of these three types are compared with electrostatic precipitators in Table 5.17-3.

Table 5.17-2. ACID MIST EMISSION FACTORS FOR SULFURIC ACID PLANTS WITHOUT CONTROLS[a]
EMISSION FACTOR RATING: B

Raw material	Oleum produced, % total output	Emissions[b] lb/ton acid	kg/MT acid
Recovered sulfur	0 to 43	0.35 to 0.8	0.175 to 0.4
Bright virgin sulfur	0	1.7	0.85
Dark virgin sulfur	33 to 100	0.32 to 6.3	0.16 to 3.15
Sulfide ores	0 to 25	1.2 to 7.4	0.6 to 3.7
Spent acid	0 to 77	2.2 to 2.7	1.1 to 1.35

[a] Reference 1.

[b] Emissions are proportional to the percentage of oleum in the total product. Use the low end of ranges for low oleum percentage and high end of ranges for high oleum percentage.

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Table 5.17-3. EMISSION COMPARISON AND COLLECTION EFFICIENCY OF TYPICAL ELECTROSTATIC PRECIPITATOR AND FIBER MIST ELIMINATORS[a]

Control device	Particle size collection efficiency, %		Acid mist emissions			
			98% acid plants[b]		oleum plants	
	>3 μm	≤3 μm	lb/ton	kg/MT	lb/ton	kg/MT
Electrostatic precipitator	99	100	0.10	0.05	0.12	0.06
Fiber mist eliminator						
Tubular	100	95 to 99	0.02	0.01	0.02	0.01
Panel	100	90 to 98	0.10	0.05	0.10	0.05
Dual pad	100	93 to 99	0.11	0.055	0.11	0.055

[a] Reference 2.

[b] Based on manufacturers' generally expected results; calculated for 8 percent sulfur dioxide concentration in gas converter.

References for Section 5.17

1. Atmospheric Emissions from Sulfuric Acid Manufacturing Processes. U.S. DHEW, PHS, National Air Pollution Control Administration. Washington, D.C. Publication Number 999-AP-13. 1966.

2. Unpublished report on control of air pollution from sulfuric acid plants. Environmental Protection Agency. Research Triangle Park, N.C. August 1971.

3. Standards of Performance for New Stationary Sources. Environmental Protection Agency. Washington, D.C. Federal Register. *36*(247): December 23, 1971.

5.18 SULFUR

By William Vatavuk

5.18.1 Process Description

Nearly all of the elemental sulfur produced from hydrogen sulfide is made by the modified Claus process. The process (Figure 5.18-1) consists of the multi-stage oxidation of hydrogen sulfide according to the following reaction:

$$\underset{\substack{\text{Hydrogen}\\\text{sulfide}}}{2H_2S} + \underset{\text{Oxygen}}{O_2} \longrightarrow \underset{\text{Sulfur}}{2S} + \underset{\text{Water}}{2H_2O}$$

In the first step, approximately one-third of the hydrogen sulfide is reacted with air in a pressurized boiler (1.0 to 1.5 atmosphere) where most of the heat of reaction and some of the sulfur are removed. After removal of the water vapor and sulfur, the cooled gases are heated to between 400 and 500°F, and passed over a "Claus" catalyst bed composed of bauxite or alumina, where the reaction is completed. The degree of reaction conpletion is a function of the number of catalytic stages employed. Two stages can recover 92 to 95 percent of the potential sulfur; three stages, 95 to 96 percent; and four stages, 96 to 97 percent. The conversion to sulfur is ultimately limited by the reverse reaction in which water vapor recombines with sulfur to form gaseous hydrogen sulfide and sulfur dioxide. Additional amounts of sulfur are lost as vapor, entrained mist, or droplets and as carbonyl sulfide and carbon disulfide (0.25 to 2.5 percent of the sulfur fed). The latter two compounds are formed in the pressurized boiler at high temperature (1500 to 2500°F) in the presence of carbon compounds.

The plant tail gas, containing the above impurities in volume quantities of 1 to 3 percent, usually passes to an incinerator, where all of the sulfur is oxidized to sulfur dioxide at temperatures ranging from 1000 to 1200°F. The tail gas containing the sulfur dioxide then passes to the atmosphere via a stack.

5.18.2 Emissions and Controls[1,2]

Virtually all of the emissions from sulfur plants consist of sulfur dioxide, the main incineration product. The quantity of sulfur dioxide emitted is, in turn, a function of the number of conversion stages employed, the process temperature and pressure, and the amounts of carbon compounds present in the pressurized boiler.

The most commonly used control method involves two main steps – conversion of sulfur dioxide to hydrogen sulfide followed by the conversion of hydrogen sulfide to elemental sulfur. Conversion of sulfur dioxide to hydrogen sulfide occurs via catalytic hydrogenation or hydrolysis at temperatures from 600 to 700°F. The products are cooled to remove the water vapor and then reacted with a sodium carbonate solution to yield sodium hydrosulfide. The hydrosulfide is oxidized to sulfur in solution by sodium vanadate. Finely divided sulfur appears as a froth that is skimmed off, washed, dried by centrifugation, and added to the plant product. Overall recovery of sulfur approaches 100 percent if this process is employed. Table 5.18-1 lists emissions from controlled and uncontrolled sulfur plants.

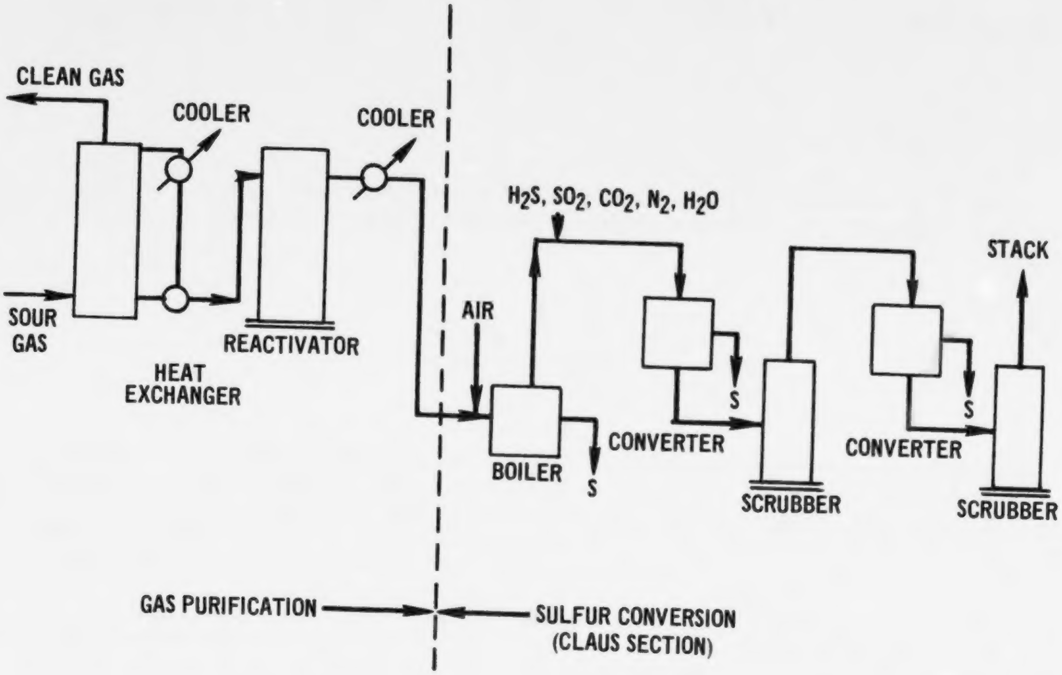
CLEAN GAS
COOLER
COOLER
SOUR GAS
HEAT EXCHANGER
REACTIVATOR
AIR
H_2S, SO_2, CO_2, N_2, H_2O
STACK
BOILER
S
CONVERTER
S
SCRUBBER
CONVERTER
S
SCRUBBER
GAS PURIFICATION
SULFUR CONVERSION (CLAUS SECTION)

Figure 5.18-1. Basic flow diagram of modified Claus process with two converter stages used in manufacturing sulfur.

Table 5.18-1. EMISSION FACTORS FOR MODIFIED-CLAUS SULFUR PLANTS EMISSION FACTOR RATING: D

Number of catalytic stages	Recovery of of sulfur, %	SO_2 emissions[a]	
		lb/ton 100% sulfur	kg/MT 100% sulfur
Two, uncontrolled	92 to 95	211 to 348	106 to 162
Three, uncontrolled	95 to 96	167 to 211	84 to 106
Four, uncontrolled	96 to 97	124 to 167	62 to 84
Sulfur removal process	99.9	4.0	2.0

[a] The range in emission factors corresponds to the range in the percentage recovery of sulfur.

References for Section 5.18

1. Beavon, David K. Abating Sulfur Plant Tail Gases. Pollution Engineering. *4*(1):34-35, January 1972.

2. Kirk-Othmer Encyclopedia of Chemical Technology, Vol. 19. New York, John Wiley and Sons, Inc. 1969.

5.19 SYNTHETIC FIBERS

5.19.1 Process Description[1]

Synthetic fibers are classified into two major categories, semi-synthetic and "true" synthetic. Semi-synthetics, such as viscose rayon and acetate fibers, result when natural polymeric materials such as cellulose are brought into a dissolved or dispersed state and then spun into fine filaments. True synthetic polymers, such as Nylon, * Orlon, and Dacron, result from addition and other polymerization reactions that form long chain molecules.

True synthetic fibers begin with the preparation of extremely long, chain-like molecules. The polymer is spun in one of four ways:[2] (1) melt spinning, in which molten polymer is pumped through spinneret jets, the polymer solidifying as it strikes the cool air; (2) dry spinning, in which the polymer is dissolved in a suitable organic solvent, and the resulting solution is forced through spinnerets; (3) wet spinning, in which the solution is coagulated in a chemical as it emerges from the spinneret; and (4) core spinning, the newest method, in which a continuous filament yarn together with short-length "hard" fibers is introduced onto a spinning frame in such a way as to form a composite yarn.

5.19.2 Emissions and Controls[1]

In the manufacture of viscose rayon, carbon disulfide and hydrogen sulfide are the major gaseous emissions. Air pollution controls are not normally used to reduce these emissions, but adsorption in activated carbon at an efficiency of 80 to 95 percent, with subsequent recovery of the CS_2 can be accomplished.[3] Emissions of gaseous hydrocarbons may also occur from the drying of the finished fiber. Table 5.19-1 presents emission factors for semi-synthetic and true synthetic fibers.

Table 5.19-1. EMISSION FACTORS FOR SYNTHETIC FIBERS MANUFACTURING
EMISSION FACTOR RATING: E

Type of fiber	Hydrocarbons		Carbon disulfide		Hydrogen sulfide		Oil vapor or mist	
	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT
Semi-synthetic								
Viscose rayon[a,b]	–	–	55	27.5	6	3	–	–
True synthetic[c]								
Nylon	7	3.5	–	–	–	–	15	7.5
Dacron	–	–	–	–	–	–	7	3.5

[a] Reference 4.

[b] May be reduced by 80 to 95 percent adsorption in activated charcoal.[3]

[c] Reference 5.

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*Mention of company or product names does not constitute endorsement by the Environmental Protection Agency.

References for Section 5.19

1. Air Pollutant Emission Factors. Final Report. Resources Research, Inc. Reston, Va. Prepared for National Air Pollution Control Administration, Durham, N.C., under Contract Number CPA-22-69-119. April 1970.

2. Fibers, Man-Made. In: Kirk-Othmer Encyclopedia of Chemical Technology. New York, John Wiley and Sons, Inc. 1969.

3. Fluidized Recovery System Nabs Carbon Disulfide. Chem. Eng. *70*(8):92-94, April 15, 1963.

4. Private communication between Resources Research, Incorporated, and Rayon Manufacturing Plant. December 1969.

5. Private communication between Resources Research, Incorporated, and E.I. Dupont de Nemours and Company. January 13, 1970.

5.20 SYNTHETIC RUBBER

5.20.1 Process Description[1]

Copolymers of butadiene and styrene, commonly known as SBR, account for more than 70 percent of all synthetic rubber produced in the United States. In a typical SBR manufacturing process, the monomers of butadiene and styrene are mixed with additives such as soaps and mercaptans. The mixture is polymerized to a conversion point of approximately 60 percent. After being mixed with various ingredients such as oil and carbon black, the latex product is coagulated and precipitated from the latex emulsion. The rubber particles are then dried and baled.

5.20.2 Emissions and Controls[1]

Emissions from the synthetic rubber manufacturing process consist of organic compounds (largely the monomers used) emitted from the reactor and blow-down tanks, and particulate matter and odors from the drying operations.

Drying operations are frequently controlled with fabric filter systems to recover any particulate emissions, which represent a product loss. Potential gaseous emissions are largely controlled by recycling the gas stream back to the process. Emission factors from synthetic rubber plants are summarized in Table 5.20-1.

Table 5.20-1. EMISSION FACTORS FOR SYNTHETIC RUBBER PLANTS: BUTADIENE-ACRYLONITRILE AND BUTADIENE-STYRENE
EMISSION FACTOR RATING: E

Compound	Emissions[a,b]	
	lb/ton	kg/MT
Alkenes		
Butadiene	40	20
Methyl propene	15	7.5
Butyne	3	1.5
Pentadiene	1	0.5
Alkanes		
Dimethylheptane	1	0.5
Pentane	2	1
Ethanenitrile	1	0.5
Carbonyls		
Acrylonitrile	17	8.5
Acrolein	3	1.5

[a] The butadiene emission is not continuous and is greatest right after a batch of partially polymerized latex enters the blow-down tank.

[b] References 2 and 3.

References for Section 5.20

1. Air Pollutant Emission Factors. Final Report. Resources Research Inc. Reston, Va. Prepared for National Air Pollution Control Administration, Durham, N.C., under Contract Number CPA-22-69-119. April 1970.

2. The Louisville Air Pollution Study. U.S. DHEW, PHS, Division of Air Pollution. Cincinnati, Ohio. 1961. p. 26-27 and 124.

3. Unpublished data from synthetic rubber plant. U.S. DHEW, PHS, EHS, National Air Pollution Control Administration, Division of Air Quality and Emissions Data. Durham, N.C. 1969.

5.21 TEREPHTHALIC ACID

5.21.1 Process Description[1,2]

The main use of terephthalic acid is to produce dimethylterephthalate, which is used for polyester fibers (like Dacron) and films. Terephthalic acid can be produced in various ways, one of which is the oxidation of *p*-xylene by nitric acid. In this process an oxygen-containing gas (usually air), *p*-xylene, and HNO_3 are all passed into a reactor where oxidation by the nitric acid takes place in two steps. The first step yields primarily N_2O; the second step yields mostly NO in the offgas. The terephthalic acid precipitated from the reactor effluent is recovered by conventional crystallization, separation, and drying operations.

5.21.2 Emissions

The NO in the offgas from the reactor is the major air contaminant from the manufacture of terephthalic acid. The amount of nitrogen oxides emitted is roughly estimated in Table 5.21-1.

Table 5.21-1. NITROGEN OXIDES EMISSION FACTORS FOR TEREPHTHALIC ACID PLANTS[a]
EMISSION FACTOR RATING: D

Type of operation	Nitrogen oxides (NO)	
	lb/ton	kg/MT
Reactor	13	6.5

[a] Reference 2.

References for Section 5.21

1. Air Pollutant Emission Factors. Final Report. Resources Research, Inc. Reston, Va. Prepared for National Air Pollution Control Administration, Durham, N.C. under Contract Number CPA-22-69-119. April 1970.
2. Terephthalic Acid. In: Kirk-Othmer Encyclopedia of Chemical Technology, Vol. 9. New York, John Wiley and Sons, Inc. 1964.

6. FOOD AND AGRICULTURAL INDUSTRY

Before food and agricultural products are used by the consumer they undergo a number of processing steps, such as refinement, preservation, and product improvement, as well as storage and handling, packaging, and shipping. This section deals with the processing of food and agricultural products and the intermediate steps that present air pollution problems. Emission factors are presented for industries where data were available. The primary pollutant emitted from these processes is particulate matter.

6.1 ALFALFA DEHYDRATING

by Tom Lahre

6.1.1 General[1-3]

Dehydrated alfalfa is a meal product resulting from the rapid drying of alfalfa by artifical means at temperatures above 212°F (100°C). Alfalfa meal is used in chicken rations, cattle feed, hog rations, sheep feed, turkey mash, and other formula feeds. It is important for its protein content, growth and reproductive factors, pigmenting xanthophylls, and vitamin contributions.

A schematic of a generalized alfalfa dehydrator plant is given in Figure 6.1-1. Standing alfalfa is mowed and chopped in the field and transported by truck to a dehydrating plant, which is usually located within 10 miles of the field. The truck dumps the chopped alfalfa (wet chops) onto a self-feeder, which carries it into a direct-fired, rotary drum. Within the drum, the wet chops are dried from an initial moisture content of about 60 to 80 percent (by weight) to about 8 to 16 percent. Typical combustion gas temperatures within the oil- or gas-fired drums range from 1800 to 2000°F (980 to 1092°C) at the inlet to 250 to 300°F (120 to 150°C) at the outlet.

From the drying drum, the dry chops are pneumatically conveyed into a primary cyclone that separates them from the high-moisture, high-temperature exhaust stream. From the primary cyclone, the chops are fed into a hammermill, which grinds the dry chops into a meal. The meal is pneumatically conveyed from the hammermill into a meal collector cyclone in which the meal is separated from the airstream and discharged into a holding bin. Meal is then fed into a pellet mill where it is steam conditioned and extruded into pellets.

From the pellet mill, the pellets are either pneumatically or mechanically conveyed to a cooler, through which air is drawn to cool the pellets and, in some cases, remove fines. Fines removal is more commonly effected in shaker screens following or ahead of the cooler, with the fines being conveyed back into the meal collector cyclone, meal bin, or pellet mill. Cyclone separators may be employed to separate entrained fines in the cooler exhaust and to collect pellets when the pellets are pneumatically conveyed from the pellet mill to the cooler.

Following cooling and screening, the pellets are transferred to bulk storage. Dehydrated alfalfa is most often stored and shipped in pellet form; however, in some instances, the pellets may be ground in a hammermill and shipped in meal form. When the finished pellets or ground pellets are pneumatically transferred to storage or loadout, additional cyclones may be employed for product airstream separation at these locations.

6.1.2 Emissions and Controls[1-3]

Particulate matter is the primary pollutant of concern from alfalfa dehydrating plants although some odors arise from the organic volatiles driven off during drying. Although the major source is the primary cooling cyclone, lesser sources include the downstream cyclone separators and the bagging and loading operations.

Emission factors for the various cyclone separators utilized in alfalfa dehydrating plants are given in Table 6.1-1. Note that, although these sources are common to many plants, there will be considerable variation from the generalized flow diagram in Figure 6.1-1 depending on the desired nature of the product, the physical layout of the plant, and the modifications made for air pollution control. Common variations include ducting the exhaust gas stream from one or more of the downstream cyclones back through the primary cyclone and ducting a portion of the primary cyclone exhaust back into the furnace. Another modification involves ducting a part of the meal collector cyclone exhaust back into the hammermill, with the remainder ducted to the primary cyclone or discharged directly to the atmosphere. Also, additional cyclones may be employed if the pellets are pneumatically rather than mechanically conveyed from the pellet mill to the cooler or if the finished pellets or ground pellets are pneumatically conveyed to storage or loadout.

Table 6.1-1. PARTICULATE EMISSION FACTORS FOR ALFALFA DEHYDRATING PLANTS
EMISSION FACTOR RATING: PRIMARY CYCLONES: A
ALL OTHER SOURCES: C

Sources[a]	Emissions	
	lb/ton of product[b]	kg/MT of product[b]
Primary cyclone	10 [c]	5 [c]
Meal collector cyclone[d]	2.6	1.3
Pellet collector cyclone[e]	Not available	Not available
Pellet cooler cyclone[f]	3	1.5
Pellet regrind cyclone[g]	8	4
Storage bin cyclone[h]	Neg.	Neg.

[a] The cyclones used for product/airstream separation are the air pollution sources in alfalfa dehydrating plants. All factors are based on References 1 and 2.

[b] Product consists of meal or pellets. These factors can be applied to the quantity of incoming wet chops by dividing by a factor of four.

[c] This average factor may be used even when other cyclone exhaust streams are ducted back into the primary cyclone. Emissions from primary cyclones may range from 3 to 35 lb/ton (1.5 to 17.5 kg/MT) of product and are more a function of the operating procedures and process modifications made for air pollution control than whether other cyclone exhausts are ducted back through the primary cyclone. Use 3 to 15 lb/ton (1.5 to 7.5 kg/MT) for plants employing good operating procedures and process modifications for air pollution control. Use higher values for older, unmodified, or less well run plants.

[d] This cyclone is also called the air meal separator or hammermill cyclone. When the meal collector exhaust is ducted back to the primary cyclone and/or the hammermill, this cyclone is no longer a source.

[e] This cyclone will only be present if the pellets are pneumatically transferred from the pellet mill to the pellet cooler.

[f] This cyclone is also called the pellet meal air separator or pellet mill cyclone. When the pellet cooler cyclone exhaust is ducted back into the primary cyclone, it is no longer a source.

[g] This cyclone is also called the pellet regrind air separator. Regrind operations are more commonly found at terminal storage facilities than at dehydrating plants.

[h] Small cyclone collectors may be used to collect the finished pellets when they are pneumatically transferred to storage.

Air pollution control (and product recovery) is accomplished in alfalfa dehydrating plants in a variety of ways. A simple, yet effective technique is the proper maintenance and operation of the alfalfa dehydrating equipment. Particulate emissions can be reduced significantly if the feeder discharge rates are uniform, if the dryer furnace is operated properly, if proper airflows are employed in the cyclone collectors, and if the hammermill is well maintained and not overloaded. It is especially important in this regard not to overdry and possibly burn the chops as this results in the generation of smoke and increased fines in the grinding and pelletizing operations.

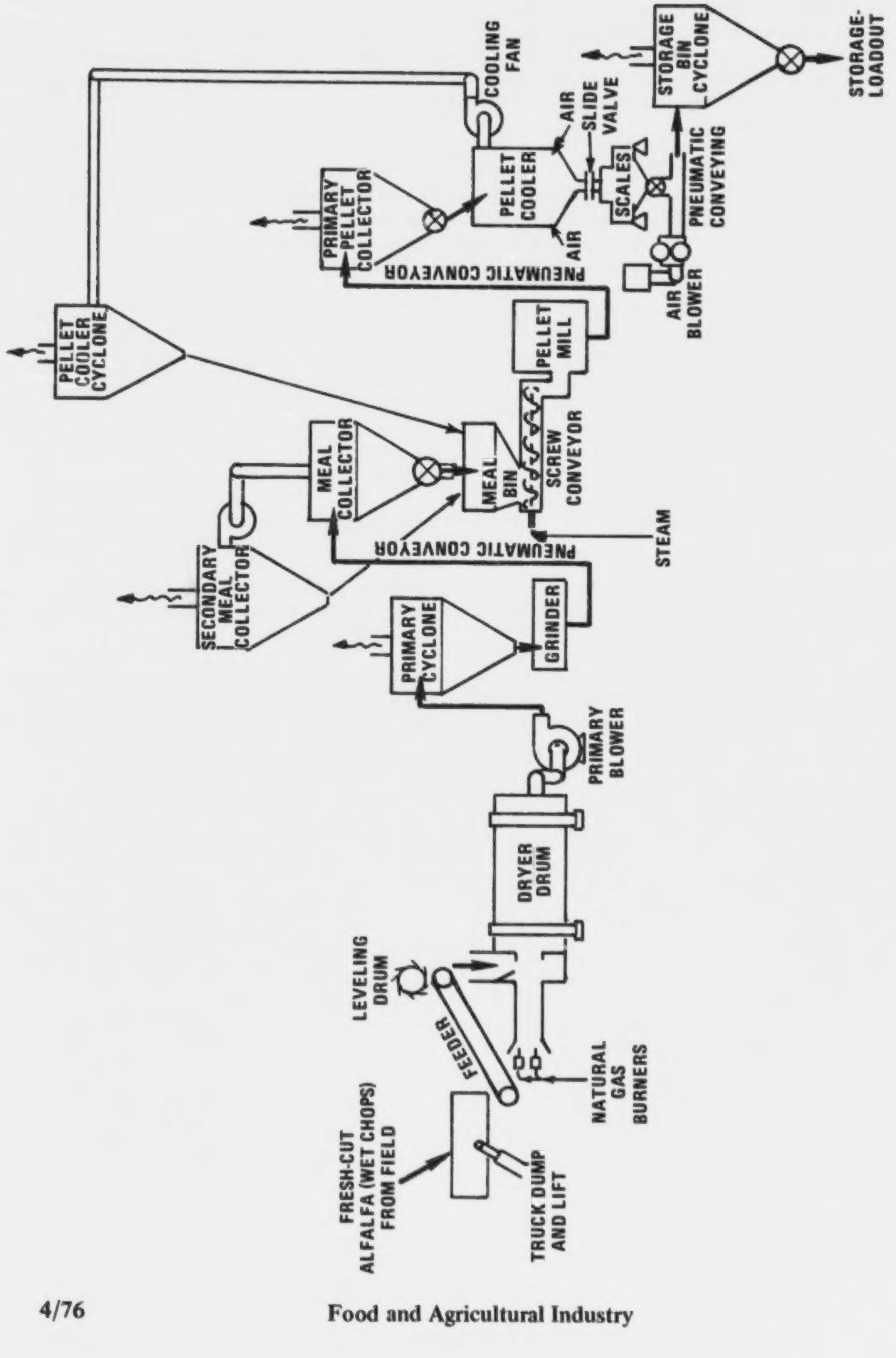
FRESH-CUT ALFALFA (WET CHOPS) FROM FIELD
TRUCK DUMP AND LIFT
FEEDER
LEVELING DRUM
NATURAL GAS BURNERS
DRYER DRUM
PRIMARY BLOWER
PRIMARY CYCLONE
GRINDER
SECONDARY MEAL COLLECTOR
PNEUMATIC CONVEYOR
MEAL COLLECTOR
STEAM
MEAL BIN
SCREW CONVEYOR
PELLET MILL
PELLET COOLER CYCLONE
PNEUMATIC CONVEYOR
PRIMARY PELLET COLLECTOR
COOLING FAN
PELLET COOLER
AIR
AIR
SLIDE VALVE
SCALES
AIR BLOWER
PNEUMATIC CONVEYING
STORAGE BIN CYCLONE
STORAGE-LOADOUT

Figure 6.1-1. Generalized flow diagram for alfalfa dehydration plant.

Equipment modification provides another means of particulate control. Existing cyclones can be replaced with more efficient cyclones and concomitant air flow systems. In addition, the furnace and burners can be modified or replaced to minimize flame impingement on the incoming green chops. In plants where the hammermill is a production bottleneck, a tendency exists to overdry the chops to increase throughput, which results in increased emissions. Adequate hammermill capacity can reduce this practice.

Secondary control devices can be employed on the cyclone collector exhaust streams. Generally, this practice has been limited to the installation of secondary cyclones or fabric filters on the meal collector, pellet collector, or pellet cooler cyclones. Some measure of secondary control can also be effected on these cyclones by ducting their exhaust streams back into the primary cyclone. Primary cyclones are not controlled by fabric filters because of the high moisture content in the resulting exhaust stream. Medium energy wet scrubbers are effective in reducing particulate emissions from the primary cyclones, but have only been installed at a few plants.

Some plants employ cyclone effluent recycle systems for particulate control. One system skims off the particulate-laden portion of the primary cyclone exhaust and returns it to the furnace for incineration. Another system recycles a large portion of the meal collector cyclone exhaust back to the hammermill. Both systems can be effective in controlling particulates but may result in operating problems, such as condensation in the recycle lines and plugging or overheating of the hammermill.

References for Section 6.1

1. Source information supplied by Ken Smith of the American Dehydrators Association, Mission, Kan. December 1975.

2. Gorman, P.G. et al. Emission Factor Development for the Feed and Grain Industry. Midwest Research Institute. Kansas City, Mo. Prepared for Environmental Protection Agency, Research Triangle Park, N.C. under Contract No. 68-02-1324. Publication No. EPA-450/3-75-054. October 1974.

3. Smith, K.D. Particulate Emissions from Alfalfa Dehydrating Plants - Control Costs and Effectiveness. Final Report. American Dehydrators Association. Mission, Kan. Prepared for Environmental Protection Agency, Research Triangle Park, N.C. Grant No. R801446. Publication No. 650/2-74-007. January 1974.

6.2 COFFEE ROASTING

6.2.1 Process Description[1,2]

Coffee, which is imported in the form of green beans, must be cleaned, blended, roasted, and packaged before being sold. In a typical coffee roasting operation, the green coffee beans are freed of dust and chaff by dropping the beans into a current of air. The cleaned beans are then sent to a batch or continuous roaster. During the roasting, moisture is driven off, the beans swell, and chemical changes take place that give the roasted beans their typical color and aroma. When the beans have reached a certain color, they are quenched, cooled, and stoned.

6.2.2 Emissions[1,2]

Dust, chaff, coffee bean oils (as mists), smoke, and odors are the principal air contaminants emitted from coffee processing. The major source of particulate emissions and practically the only source of aldehydes, nitrogen oxides, and organic acids is the roasting process. In a direct-fired roaster, gases are vented without recirculation through the flame. In the indirect-fired roaster, however, a portion of the roaster gases are recirculated and particulate emissions are reduced. Emissions of both smoke and odors from the roasters can be almost completely removed by a properly designed afterburner.[1,2]

Particulate emissions also occur from the stoner and cooler. In the stoner, contaminating materials heavier than the roasted beans are separated from the beans by an air stream. In the cooler, quenching the hot roasted beans with water causes emissions of large quantities of steam and some particulate matter.[3] Table 6.2-1 summarizes emissions from the various operations involved in coffee processing.

Table 6.2-1. EMISSION FACTORS FOR ROASTING PROCESSES WITHOUT CONTROLS
EMISSION FACTOR RATING: B

Type of process	Pollutant							
	Particulates[a]		NO_x[b]		Aldehydes[b]		Organic acids[b]	
	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT
Roaster								
Direct-fired	7.6	3.8	0.1	0.05	0.2	0.1	0.9	0.45
Indirect-fired	4.2	2.1	0.1	0.05	0.2	0.1	0.9	0.45
Stoner and cooler[c]	1.4	0.7	–	–	–	–	–	–
Instant coffee spray dryer	1.4[d]	0.7[d]	–	–	–	–	–	–

[a] Reference 3.
[b] Reference 1.
[c] If cyclone is used, emissions can be reduced by 70 percent.
[d] Cyclone plus wet scrubber always used, representing a controlled factor.

References for Section 6.2

1. Polglase, W.L., H.F. Dey, and R.T. Walsh. Coffee Processing. In: Air Pollution Engineering Manual. Danielson, J.A. (ed.). U.S. DHEW, PHS, National Center for Air Pollution Control. Cincinnati, Ohio. Publication Number 999-AP-40. 1967. p. 746-749.

2. Duprey, R.L. Compilation of Air Pollutant Emission Factors. U.S. DHEW, PHS, National Center for Air Pollution Control. Durham, N.C. PHS Publication Number 999-AP-42. 1968. p. 19-20.

3. Partee, F. Air Pollution in the Coffee Roasting Industry. Revised Ed. U.S. DHEW, PHS, Division of Air Pollution. Cincinnati, Ohio. Publication Number 999-AP-9. 1966.

6.3 COTTON GINNING

6.3.1 General[1]

The primary function of a cotton gin is to take raw seed cotton and separate the seed and the lint. A large amount of trash is found in the seed cotton, and it must also be removed. The problem of collecting and disposing of gin trash is two-fold. The first problem consists of collecting the coarse, heavier trash such as burrs, sticks, stems, leaves, sand, and dirt. The second problem consists of collecting the finer dust, small leaf particles, and fly lint that are discharged from the lint after the fibers are removed from the seed. From 1 ton (0.907 MT) of seed cotton, approximately one 500-pound (226-kilogram) bale of cotton can be made.

6.3.2 Emissions and Controls

The major sources of particulates from cotton ginning include the unloading fan, the cleaner, and the stick and burr machine. From the cleaner and stick and burr machine, a large percentage of the particles settle out in the plant, and an attempt has been made in Table 6.3-1 to present emission factors that take this into consideration. Where cyclone collectors are used, emissions have been reported to be about 90 percent less.[1]

Table 6.3-1. EMISSION FACTORS FOR COTTON GINNING OPERATIONS WITHOUT CONTROLS[a,b]
EMISSION FACTOR RATING: C

Process	Estimated total particulates		Particles > 100 μm settled out, %	Estimated emission factor (released to atmosphere)	
	lb/bale	kg/bale		lb/bale	kg/bale
Unloading fan	5	2.27	0	5.0	2.27
Cleaner	1	0.45	70	0.30	0.14
Stick and burr machine	3	1.36	95	0.20	0.09
Miscellaneous	3	1.36	50	1.5	0.68
Total	12	5.44	–	7.0	3.2

[a] References 1 and 2.
[b] One bale weighs 500 pounds (226 kilograms).

References for Section 6.3

1. Air-Borne Particulate Emissions from Cotton Ginning Operations. U.S. DHEW, PHS, Taft Sanitary Engineering Center. Cincinnati, Ohio. 1960.

2. Control and Disposal of Cotton Ginning Wastes. A Symposium Sponsored by National Center for Air Pollution Control and Agricultural Research Service, Dallas, Texas. May 1966.

6.4 FEED AND GRAIN MILLS AND ELEVATORS

6.4.1 General[1-3]

Grain elevators are buildings in which grains are gathered, stored, and discharged for use, further processing, or shipping. They are classified as "country," "terminal," and "export" elevators, according to their purpose and location. At country elevators, grains are unloaded, weighed, and placed in storage as they are received from farmers residing within about a 20-mile radius of the elevator. In addition, country elevators sometimes dry or clean grain before it is shipped to terminal elevators or processors.

Terminal elevators receive most of their grain from country elevators and ship to processors, other terminals, and exporters. The primary functions of terminal elevators are to store large quantities of grain without deterioration and to dry, clean, sort, and blend different grades of grain to meet buyer specifications.

Export elevators are similar to terminal elevators except that they mainly load grain on ships for export.

Processing of grain in mills and feed plants ranges from very simple mixing steps to complex industrial processes. Included are such diverse processes as: (1) simple mixing operations in feed mills, (2) grain milling in flour mills, (3) solvent extracting in soybean processing plants, and (4) a complex series of processing steps in a corn wet-milling plant.

6.4.2 Emissions and Controls

Grain handling, milling, and processing include a variety of operations from the initial receipt of the grain at either a country or terminal elevator to the delivery of a finished product. Flour, livestock feed, soybean oil, and corn syrup are among the products produced from plants in the grain and feed industry. Emissions from the feed and grain industry can be separated into two general areas, those occurring at grain elevators and those occurring at grain processing operations.

6.4.2.1 Grain Elevators - Grain elevator emissions can occur from many different operations in the elevator including unloading (receiving), loading (shipping), drying, cleaning, headhouse (legs), tunnel belt, gallery belt, and belt trippers. Emission factors for these operations at terminal, country, and export elevators are presented in Table 6.4-1. All of these emission factors are approximate average values intended to reflect a variety of grain types. Actual emission factors for a specific source may be considerably different, depending on the type of grain, i.e., corn, soybeans, wheat, and other factors such as grain quality.

The emission factors shown in Table 6.4-1 represent the amount of dust generated per ton of grain processed through each of the designated operations (i.e., uncontrolled emission factors). Amounts of grain processed through each of these operations in a given elevator are dependent on such factors as the amount of grain turned (interbin transfer), amount dryed, and amount cleaned, etc. Because the amount of grain passing through each operation is often difficult to determine, it may be more useful to express the emission factors in terms of the amount of grain shipped or received, assuming these amounts are about the same over the long term. Emission factors from Table 6.4-1 have been modified accordingly and are shown in Table 6.4-2 along with the appropriate multiplier that was used as representative of typical ratios of throughput at each operation to the amount of grain shipped or received. This ratio is an approximate value based on average values for turning, cleaning, and drying in each type of elevator. However, because operating practices in individual elevators are different, these ratios, like the basic emission factors themselves, are more valid when applied to a group of elevators rather than individual elevators.

Table 6.4-1. PARTICULATE EMISSION FACTORS FOR UNCONTROLLED GRAIN ELEVATORS
EMISSION FACTOR RATING: B

Type of source	Emission factor[a]	
	lb/ton	kg/MT
Terminal elevators		
Unloaded (receiving)	1.0	0.5
Loading (shipping)	0.3	0.2
Removal from bins (tunnel belt)	1.4	1.7
Drying[b]	1.1	0.6
Cleaning[c]	3.0	1.5
Headhouse (legs)	1.5	0.8
Tripper (gallery belt)	1.0	0.5
Country elevators		
Unloading (receiving)	0.6	0.3
Loading (shipping)	0.3	0.2
Removal from bins	1.0	0.5
Drying[b]	0.7	0.4
Cleaning[c]	3.0	1.5
Headhouse (legs)	1.5	0.8
Export elevators		
Unloading (receiving)	1.0	0.5
Loading (shipping)	1.0	0.5
Removal from bins (tunnel belt)	1.4	0.7
Drying[b]	1.1	0.5
Cleaning[c]	3.0	1.5
Headhouse (legs)	1.5	0.8
Tripper (gallery belts)	1.0	0.5

[a] Emission factors are in terms of pounds of dust emitted per ton of grain processed by each operation. Most of the factors for terminal and export elevators are based on Reference 1. Emission factors for drying are based on References 2 and 3. The emission factors for country elevators are based on Reference 1 and specific country elevator test data in References 4 through 9.

[b] Emission factors for drying are based on 1.8 lb/ton for rack dryers and 0.3 lb/ton for column dryers prorated on the basis of distribution of these two types of dryers in each elevator category, as discussed in Reference 3.

[c] Emission factor of 3.0 for cleaning is an average value which may range from <0.5 for wheat up to 6.0 for corn.

The factors in Tables 6.4-1 or 6.4-2 should not be added together in an attempt to obtain a single emission factor value for grain elevators because in most elevators some of the operations are equipped with control devices and some are not. Therefore, any estimation of emissions must be directed to each operation and its associated control device, rather than the elevator as a whole, unless the purpose was to estimate total potential (i.e., uncontrolled) emissions. An example of the use of emission factors in making an emission inventory is contained in Reference 3.

Table 6.4-2. PARTICULATE EMISSION FACTORS FOR GRAIN ELEVATORS BASED ON AMOUNT OF GRAIN RECEIVED OR SHIPPED[a]

Type of source	Emission factor, lb/ton processed	x	Typical ratio of tons processed to tons received or shipped[d]	=	Emission factor, lb/ton received or shipped
Terminal elevators					
Unloading (receiving)	1.0		1.0		1.0
Loading (shipping)	0.3		1.0		0.3
Removal from bins (tunnel belt)	1.4		2.0		2.8
Drying[b]	1.1		0.1		0.1
Cleaning[c]	3.0		0.2		0.6
Headhouse (legs)	1.5		3.0		4.5
Tripper (gallery belt)	1.0		1.7		1.7
Country elevators					
Unloading (receiving)	0.6		1.0		0.6
Loading (shipping)	0.3		1.0		0.3
Removal from bins	1.0		2.1		2.1
Drying[b]	0.7		0.3		0.2
Cleaning[c]	3.0		0.1		0.3
Headhouse (legs)	1.5		3.1		4.7
Export elevators					
Unloading (receiving)	1.0		1.0		1.0
Loading (shipping)	1.0		1.0		1.0
Removal from bins (tunnel belt)	1.4		1.2		1.7
Drying[b]	1.1		0.01		0.01
Cleaning[c]	3.0		0.2		0.6
Headhouse (legs)	1.5		2.2		3.3
Tripper (gallery belt)	1.0		1.1		1.1

[a] Assume that over the long term the amount received is approximately equal to amount shipped.

[b] See Note[b] in Table 6.4-1.

[c] See Note[c] in Table 6.4-1.

[d] Ratios shown are average values taken from a survey of many elevators across the U.S.[3] These ratios can be considerably different for any individual elevator or group of elevators in the same locale.

Some of the operations listed in the table, such as the tunnel belt and belt tripper, are internal or in-house dust sources which, if uncontrolled, might show lower than expected atmospheric emissions because of internal settling of dust. The reduction in emissions via internal settling is not known, although it is possible that all of this dust is eventually emitted to the atmosphere due to subsequent external operations, internal ventilation, or other means.

Many elevators utilize control devices on at least some operations. In the past, cyclones have commonly been applied to legs in the headhouse and tunnel belt hooding systems. More recently, fabric filters have been utilized at many elevators on almost all types of operations. Unfortunately, some sources in grain elevators present control problems. Control of loadout operations is difficult because of the problem of containment of the emissions. Probably the most difficult operation to control, because of the large flow rate and high moisture content of the exhaust gases, is the dryers. Screenhouses or continuously vacuumed screen systems are available for reducing dryer emissions and have been applied at several facilities. Detailed descriptions of dust control systems for grain elevator operations are contained in Reference 2.

6.4.2.2 **Grain Processing Operations** - Grain processing operations include many of the operations performed in a grain elevator in addition to milling and processing of the grain. Emission factors for different grain milling and processing operations are presented in Table 6.4-3. Brief discussions of these different operations and the methods used for arriving at the emission factor values shown in Table 6.4-3 are presented below.

Table 6.4-3. PARTICULATE EMISSION FACTORS FOR GRAIN PROCESSING OPERATIONS[1,2,3]
EMISSION FACTOR RATING: D

Type of source	Emission factor[a,b] (uncontrolled except where indicated)	
	lb/ton	kg/MT
Feed mills		
Receiving	1.30	0.65
Shipping	0.50	0.25
Handling	3.00	1.50
Grinding	0.10[c]	0.05[c]
Pellet coolers	0.10[c]	0.05[c]
Wheat mills		
Receiving	1.00	0.50
Precleaning and handling	5.00	2.50
Cleaning house	-	-
Millhouse	70.00	35.00
Durum mills		
Receiving	1.00	0.50
Precleaning and handling	5.00	2.50
Cleaning house	-	-
Millhouse	-	-
Rye milling		
Receiving	1.00	0.50
Precleaning and handling	5.00	2.50
Cleaning house	-	-
Millhouse	70.00	35.00
Dry corn milling		
Receiving	1.00	0.50
Drying	0.50	0.25
Precleaning and handling	5.00	2.50
Cleaning house	6.00	3.00
Degerming and milling	-	-
Oat milling		
Total	2.50[d]	1.25[d]
Rice milling		
Receiving	0.64	0.32
Handling and precleaning	5.00	2.50
Drying	-	-
Cleaning and millhouse	-	-
Soybean mills		
Receiving	1.60	0.80
Handling	5.00	2.50
Cleaning	-	-
Drying	7.20	3.60
Cracking and dehulling	3.30	1.65
Hull grinding	2.00	1.00

Table 6.4-3 (continued). PARTICULATE EMISSION FACTORS FOR GRAIN PROCESSING OPERATIONS[1,2,3]
EMISSION FACTOR RATING: D

Type of source	Emission factor[a,b] (uncontrolled except where indicated) lb/ton	kg/MT
Bean conditioning	0.10	0.05
Flaking	0.57	0.29
Meal dryer	1.50	0.75
Meal cooler	1.80	0.90
Bulk loading	0.27	0.14
Corn wet milling		
Receiving	1.00	0.50
Handling	5.00	2.50
Cleaning	6.00	3.00
Dryers	-	-
Bulk loading	-	-

[a] Emission factors are expressed in terms of pounds of dust emitted per ton of grain entering the plant (i.e., received), which is not necessarily the same as the amount of material processed by each operation.

[b] Blanks indicate insufficient information.

[c] Controlled emission factor (controlled with cyclones).

[d] Controlled emission factor.(This represents several sources in one plant; some controlled with cyclones and others controlled with fabric filters.)

Emission factor data for feed mill operations are sparse. This is partly due to the fact that many ingredients, whole grain and other dusty materials (bran, dehydrated alfalfa, etc.), are received by both truck and rail and several unloading methods are employed. However, because some feed mill operations (handling, shipping, and receiving) are similar to operations in a grain elevator, an emission factor for each of these different operations was estimated on that basis. The remaining operations are based on information in Reference 2.

Three emission areas for wheat mill processing operations are grain receiving and handling, cleaning house, and milling operations. Data from Reference 1 are used to estimate emissions factors for grain receiving and handling. Data for the cleaning house are insufficient to estimate an emission factor, and information contained in Reference 2 is used to estimate the emission factor for milling operations. The large emission factor for the milling operation is somewhat misleading because almost all of the sources involved are equipped with control devices to prevent product losses; fabric filters are widely used for this purpose.

Operations for durum mills and rye milling are similar to those of wheat milling. Therefore, most of these emission factors are assumed equal to those for wheat mill operations.

The grain unloading, handling, and cleaning operations for dry corn milling are similar to those in other grain mills, but the subsequent operations are somewhat different. Also, some drying of corn received at the mill may be necessary prior to storage. An estimate of the emission factor for drying is obtained from Reference 2. Insufficient information is available to estimate emission factors for degerming and milling.

Information necessary to estimate emissions from oat milling is unavailable, and no emission factor for another grain is considered applicable because oats are reported to be dustier than many other grains. The only emission factor data available are for controlled emissions.[2] An overall controlled emission factor of 2.5 lb/ton is calculated from these data.

Emission factors for rice milling are based on those for similar operations in other grain handling facilities. Insufficient information is available to estimate emission factors for drying, cleaning, and mill house operations.

Information contained in Reference 2 is used to estimate emission factors for soybean mills.

Emissions information on corn wet-milling is unavailable in most cases due to the wide variety of products and the diversity of operations. Receiving, handling, and cleaning operations emission factors are assumed to be similar to those for dry corn milling.

Many of the operations performed in grain milling and processing plants are the same as those in grain elevators, so the control methods are similar. As in the case of grain elevators, these plants often use cyclones or fabric filters to control emissions from the grain handling operations (e.g., unloading, legs, cleaners, etc.). These same devices are also often used to control emissions from other processing operations; a good example of this is the extensive use of fabric filters in flour mills. However, there are also certain operations within some milling operations that are not amenable to use of these devices. Therefore, wet scrubbers have found some application, particularly where the effluent gas stream has a high moisture content. Certain other operations have been found to be especially difficult to control, such as rotary dryers in wet corn mills. Descriptions of the emission control systems that have been applied to operations within the grain milling and processing industries are contained in Reference 2.

This section was prepared for EPA by Midwest Research Institute.[10]

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2. Shannon, L.J. et al. Emission Control in the Grain and Feed Industry , Volume I - Engineering and Cost Study. Final Report. Prepared for Environmental Protection Agency by Midwest Research Institute. Document No. EPA-450/3-73-003a. Research Triangle Park, N.C. December 1973.

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6. Belgea, F.J. Cyclone Emissions and Efficiency Evaluation. Report submitted to North Dakota State Department of Health on tests at an elevator in Edenburg, North Dakota, by Pollution Curbs, Inc. St. Paul, Minnesota. March 10, 1972.

7. Trowbridge, A.L. Particulate Emission Testing - ERC Report No. 4-7683. Report submitted to North Dakota State Department of Health on tests at an elevator in Egeland, North Dakota, by Environmental Research Corporation. St. Paul, Minnesota. January 16, 1976.

8. Belgea, F.J. Grain Handling Dust Collection Systems Evaluation for Farmers Elevator Company, Minot, North Dakota. Report submitted to North Dakota State Department of Health, by Pollution Curbs, Inc. St. Paul, Minnesota. August 28, 1972.

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6.5 FERMENTATION

6.5.1 Process Description[1]

For the purpose of this report only the fermentation industries associated with food will be considered. This includes the production of beer, whiskey, and wine.

The manufacturing process for each of these is similar. The four main brewing production stages and their respective sub-stages are: (1) brewhouse operations, which include (a) malting of the barley, (b) addition of adjuncts (corn, grits, and rice) to barley mash, (c) conversion of starch in barley and adjuncts to maltose sugar by enzymatic processes, (d) separation of wort from grain by straining, and (e) hopping and boiling of the wort; (2) fermentation, which includes (a) cooling of the wort, (b) additional yeast cultures, (c) fermentation for 7 to 10 days, (d) removal of settled yeast, and (e) filtration and carbonation; (3) aging, which lasts from 1 to 2 months under refrigeration; and (4) packaging, which includes (a) bottling-pasteurization, and (b) racking draft beer.

The major differences between beer production and whiskey production are the purification and distillation necessary to obtain distilled liquors and the longer period of aging. The primary difference between wine making and beer making is that grapes are used as the initial raw material in wine rather than grains.

6.5.2 Emissions[1]

Emissions from fermentation processes are nearly all gases and primarily consist of carbon dioxide, hydrogen, oxygen, and water vapor, none of which present an air pollution problem. Emissions of particulates, however, can occur in the handling of the grain for the manufacture of beer and whiskey. Gaseous hydrocarbons are also emitted from the drying of spent grains and yeast in beer and from the whiskey-aging warehouses. No significant emissions have been reported for the production of wine. Emission factors for the various operations associated with beer, wine, and whiskey production are shown in Table 6.5-1.

Table 6.5-1. EMISSION FACTORS FOR FERMENTATION PROCESSES
EMISSION FACTOR RATING: E

Type of product	Particulates		Hydrocarbons	
	lb/ton	kg/MT	lb/ton	kg/MT
Beer				
Grain handling[a]	3	1.5	–	–
Drying spent grains, etc.[a]	5	2.5	NA[b]	NA
Whiskey				
Grain handling[a]	3	1.5	–	–
Drying spent grains, etc.[a]	5	2.5	NA	NA
Aging	–	–	10[c]	0.024[d]
Wine	Neg[e]	Neg	Neg[e]	Neg

[a] Based on section on grain processing.
[b] No emission factor available, but emissions do occur.
[c] Pounds per year per barrel of whiskey stored.[2]
[d] Kilograms per year per liter of whiskey stored.
[e] No significant emissions.

References for Section 6.5

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2. Shreve, R.N. Chemical Process Industries, 3rd Ed. New York, McGraw-Hill Book Company. 1967. p. 591-608.

6.6 FISH PROCESSING

revised by Susan Sercer

6.6.1 Process Description

Fish processing includes the canning of fish and the manufacturing of by-products such as fish oil and fish meal. The manufacturing of fish oil and fish meal are known as reduction processes. A generalized fish processing operation is presented in Figure 6.6-1 .

Two types of canning operations are used. One is the "wet fish" method in which trimmed and eviscerated fish are cooked directly in open cans. The other operation is the "pre-cooked" process in which eviscerated fish are cooked whole and portions are hand selected and packed into cans. The pre-cooked process is used primarily for larger fish such as tuna.

By-product manufacture of rejected whole fish and scrap requires several steps. First, the fish scrap mixture from the canning line is charged to a live steam cooker. After the material leaves the cooker, it is pressed to remove water and oil. The resulting press cake is broken up and dried in a rotary drier.

Two types of driers are used to dry the press cake: direct-fired and steam-tube driers. Direct-fired driers contain a stationary firebox ahead of the rotating section. The hot products of combustion from the firebox are mixed with air and wet meal inside the rotating section of the drier. Exhaust gases are generally vented to a cyclone separator to recover much of the entrained fish meal product. Steam-tube driers contain a cylindrical bank of rotating tubes through which hot, pressurized steam is passed. Heat is indirectly transferred to the meal and the air from the hot tubes. As with direct-fired driers, the exhaust gases are vented to a cyclone for product recovery.

6.6.2 Emissions and Controls

Although smoke and dust can be a problem, odors are the most objectionable emissions from fish processing plants. By-product manufacture results in more of these odorous contaminants than cannery operations because of the greater state of decomposition of the materials processed. In general, highly decayed feedstocks produce greater concentrations of odors than do fresh feedstocks.

The largest odor sources are the fish meal driers. Usually, direct-fired driers emit more odors than steam-tube driers. Direct-fired driers will also emit smoke, particularly if the driers are operated under high temperature conditions. Cyclones are frequently employed on drier exhaust gases for product recovery and particulate emission control.

Odorous gases from reduction cookers consist primarily of hydrogen sulfide [H_2S] and trimethylamine [$(CH_3)_3N$]. Odors from reduction cookers are emitted in volumes appreciably less than from fish meal driers. There are virtually no particulate emissions from reduction cookers.

Some odors are also produced by the canning processes. Generally, the pre-cooked process emits less odorous gases than the wet-fish process. This is because in the pre-cooked process, the odorous exhaust gases are trapped in the cookers, whereas in the wet-fish process, the steam and odorous offgases are commonly vented directly to the atmosphere.

Fish cannery and fish reduction odors can be controlled with afterburners, chlorinator-scrubbers, and condensers. Afterburners are most effective, providing virtually 100 percent odor control; however they are costly from a fuel-use standpoint. Chlorinator-scrubbers have been found to be 95 to 99 percent effective in controlling odors from cookers and driers. Condensers are the least effective control device. Generally, centrifugal collectors are satisfactory for controlling excessive dust emissions from driers.

Emission factors for fish processing are presented in Table 6.6-1.

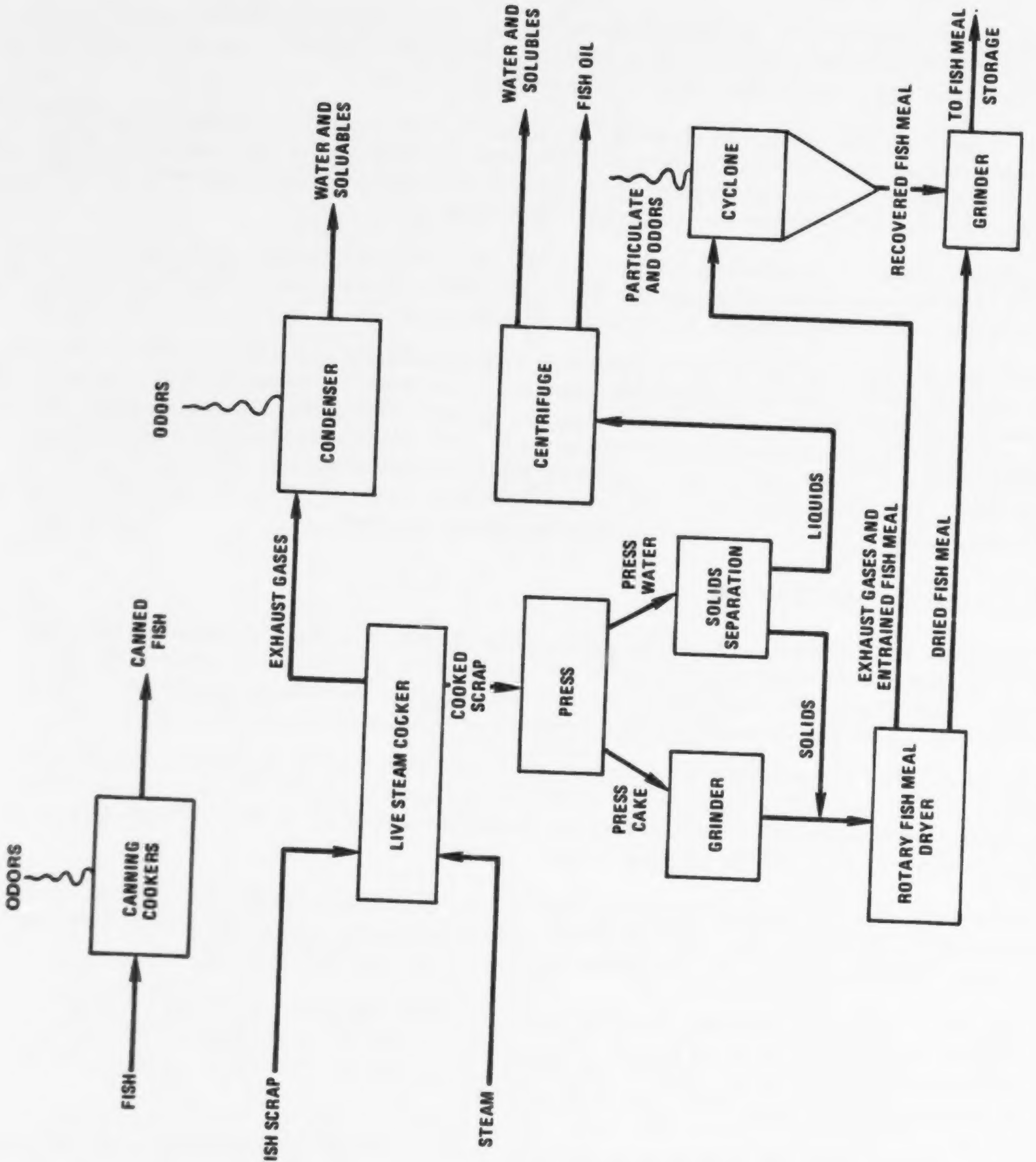
FISH
ODORS
CANNING COOKERS
CANNED FISH
FISH SCRAP
STEAM
LIVE STEAM COCKER
EXHAUST GASES
ODORS
CONDENSER
WATER AND SOLUABLES
COOKED SCRAP
PRESS
PRESS WATER
PRESS CAKE
SOLIDS SEPARATION
LIQUIDS
CENTRIFUGE
WATER AND SOLUBLES
FISH OIL
GRINDER
SOLIDS
ROTARY FISH MEAL DRYER
EXHAUST GASES AND ENTRAINED FISH MEAL
DRIED FISH MEAL
PARTICULATE AND ODORS
CYCLONE
RECOVERED FISH MEAL
GRINDER
TO FISH MEAL STORAGE

Figure 6.6-1. A generalized fish processing flow diagram.

Table 6.6-1. EMISSION FACTORS FOR FISH PROCESSING PLANTS
EMISSION FACTOR RATING: C

Emission source	Particulates		Trimethylamine $(CH_3)_3N$		Hydrogen sulfide (H_2S)	
	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT
Cookers, canning	Neg.[a]	Neg.[a]	NA[b]	NA[b]	NA[b]	NA[b]
Cookers, fish scrap						
Fresh fish	Neg.[a]	Neg.[a]	0.3[c]	0.15[c]	0.01[c]	0.005[c]
Stale fish	Neg.[a]	Neg.[a]	3.5[c]	1.75[c]	0.2[c]	0.10[c]
Dryers	0.1[d]	0.05[d]	NA[d]	NA[d]	NA[d]	NA[d]

[a] Reference 1.

[b] Although it is known that odors are emitted from canning cookers, quantitative estimates are not available.

[c] Reference 2.

[d] Limited data suggest that there is not much difference in particulate emissions between steam tube and direct-fired dryers. Based on reference 1.

References for Section 6.6

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6.7 MEAT SMOKEHOUSES

6.7.1 Process Description[1]

Smoking is a diffusion process in which food products are exposed to an atmosphere of hardwood smoke, causing various organic compounds to be absorbed by the food. Smoke is produced commerically in the United States by three major methods: (1) by burning dampened sawdust (20 to 40 percent moisture), (2) by burning dry sawdust (5 to 9 percent moisture) continuously, and (3) by friction. Burning dampened sawdust and kiln-dried sawdust are the most widely used methods. Most large, modern, production meat smokehouses are the recirculating type, in which smoke is circulated at reasonably high temperatures throughout the smokehouse.

6.7.2 Emissions and Controls[1]

Emissions from smokehouses are generated from the burning hardwood rather than from the cooked product itself. Based on approximately 110 pounds of meat smoked per pound of wood burned (110 kilograms of meat per kilogram of wood burned), emission factors have been derived for meat smoking and are presented in Table 6.7-1.

Emissions from meat smoking are dependent on several factors, including the type of wood, the type of smoke generator, the moisture content of the wood, the air supply, and the amount of smoke recirculated. Both low-voltage electrostatic precipitators and direct-fired afterburners may be used to reduce particulate and organic emissions. These controlled emission factors have also been shown in Table 6.7-1.

Table 6.7-1. EMISSION FACTORS FOR MEAT SMOKING[a,b]
EMISSION FACTOR RATING: D

Pollutant	Uncontrolled		Controlled[c]	
	lb/ton of meat	kg/MT of meat	lb/ton of meat	kg/MT of meat
Particulates	0.3	0.15	0.1	0.05
Carbon monoxide	0.6	0.3	Neg[d]	Neg
Hydrocarbons (CH_4)	0.07	0.035	Neg	Neg
Aldehydes (HCHO)	0.08	0.04	0.05	0.025
Organic acids (acetic)	0.2	0.10	0.1	0.05

[a] Based on 110 pounds of meat smoked per pound of wood burned (110 kg meat/kg wood burned).
[b] References 2, 3, and section on charcoal production.
[c] Controls consist of either a wet collector and low-voltage precipitator in series or a direct-fired afterburner.
[d] With afterburner.

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References for Section 6.7

1. Air Pollutant Emission Factors. Final Report. Resources Research, Inc. Reston, Va. Prepared for National Air Pollution Control Administration, Durham, N.C., under Contract Number CPA-22-69-119. April 1970.

2. Carter, E. Private communication between Maryland State Department of Health and Resources Research, Incorporated. November 21, 1969.

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6.8 NITRATE FERTILIZERS

6.8.1 General[1,2]

For this report, nitrate fertilizers are defined as the product resulting from the reaction of nitric acid and ammonia to form ammonium nitrate solutions or granules. Essentially three steps are involved in producing ammonium nitrate: neutralization, evaporation of the neutralized solution, and control of the particle size and characteristics of the dry product.

Anhydrous ammonia and nitric acid (57 to 65 percent HNO_3)[3,4] are brought together in the neutralizer to produce ammonium nitrate. An evaporator or concentrator is then used to increase the ammonium nitrate concentration. The resulting solutions may be formed into granules by the use of prilling towers or by ordinary granulators. Limestone may be added in either process in order to produce calcium ammonium nitrate.[5,6]

6.8.2 Emissions and Controls

The main emissions from the manufacture of nitrate fertilizers occur in the neutralization and drying operations. By keeping the neutralization process on the acidic side, losses of ammonia and nitric oxides are kept at a minimum. Nitrate dust or particulate matter is produced in the granulation or prilling operation. Particulate matter is also produced in the drying, cooling, coating, and material handling operations. Additional dust may escape from the bagging and shipping facilities.

Typical operations do not use collection devices on the prilling tower. Wet or dry cyclones, however, are used for various granulating, drying, or cooling operations in order to recover valuable products. Table 6.8-1 presents emission factors for the manufacture of nitrate fertilizers.

Table 6.8-1. EMISSION FACTORS FOR NITRATE FERTILIZER MANUFACTURING WITHOUT CONTROLS
EMISSION FACTOR RATING: B

Type of process[a]	Particulates		Nitrogen oxides (NO_3)		Ammonia	
	lb/ton	kg/MT	lb/ton	kg/MT	lb/ton	kg/MT
With prilling tower[b]						
Neutralizer[c,d]	–	–	–	–	2	1
Prilling tower	0.9	0.45	–	–	–	–
Dryers and coolers[e]	12	6	–	–	–	–
With granulator[b]						
Neutralizer[c,d]	–	–	–	–	2	1
Granulator[e]	0.4	0.2	0.9	0.45	0.5	0.25
Dryers and coolers[e,f]	7	3.5	3	1.5	1.3	0.65

[a] Plants will use either a prilling tower or a granulator but not both.
[b] Reference 7.
[c] Reference 8.
[d] Controlled factor based on 95 percent recovery in recycle scrubber.
[e] Use of wet cyclones can reduce emissions by 70 percent.
[f] Use of wet-screen scrubber following cyclone can reduce emissions by 95 to 97 percent.

References for Section 6.8

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5. Ellwood, P. Nitrogen Fertilizer Plant Integrates Dutch and American Know-How. Chem. Eng. p. 136-138, May 11, 1964.

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6.9 ORCHARD HEATERS

by Dennis H. Ackerson

6.9.1 General[1-6]

Orchard heaters are commonly used in various areas of the United States to prevent frost damage to fruit and fruit trees. The five common types of orchard heaters—pipeline, lazy flame, return stack, cone, and solid fuel—are shown in Figure 6.9-1. The pipeline heater system is operated from a central control and fuel is distributed by a piping system from a centrally located tank. Lazy flame, return stack, and cone heaters contain integral fuel reservoirs, but can be converted to a pipeline system. Solid fuel heaters usually consist only of solid briquettes, which are placed on the ground and ignited.

The ambient temperature at which orchard heaters are required is determined primarily by the type of fruit and stage of maturity, by the daytime temperatures, and by the moisture content of the soil and air.

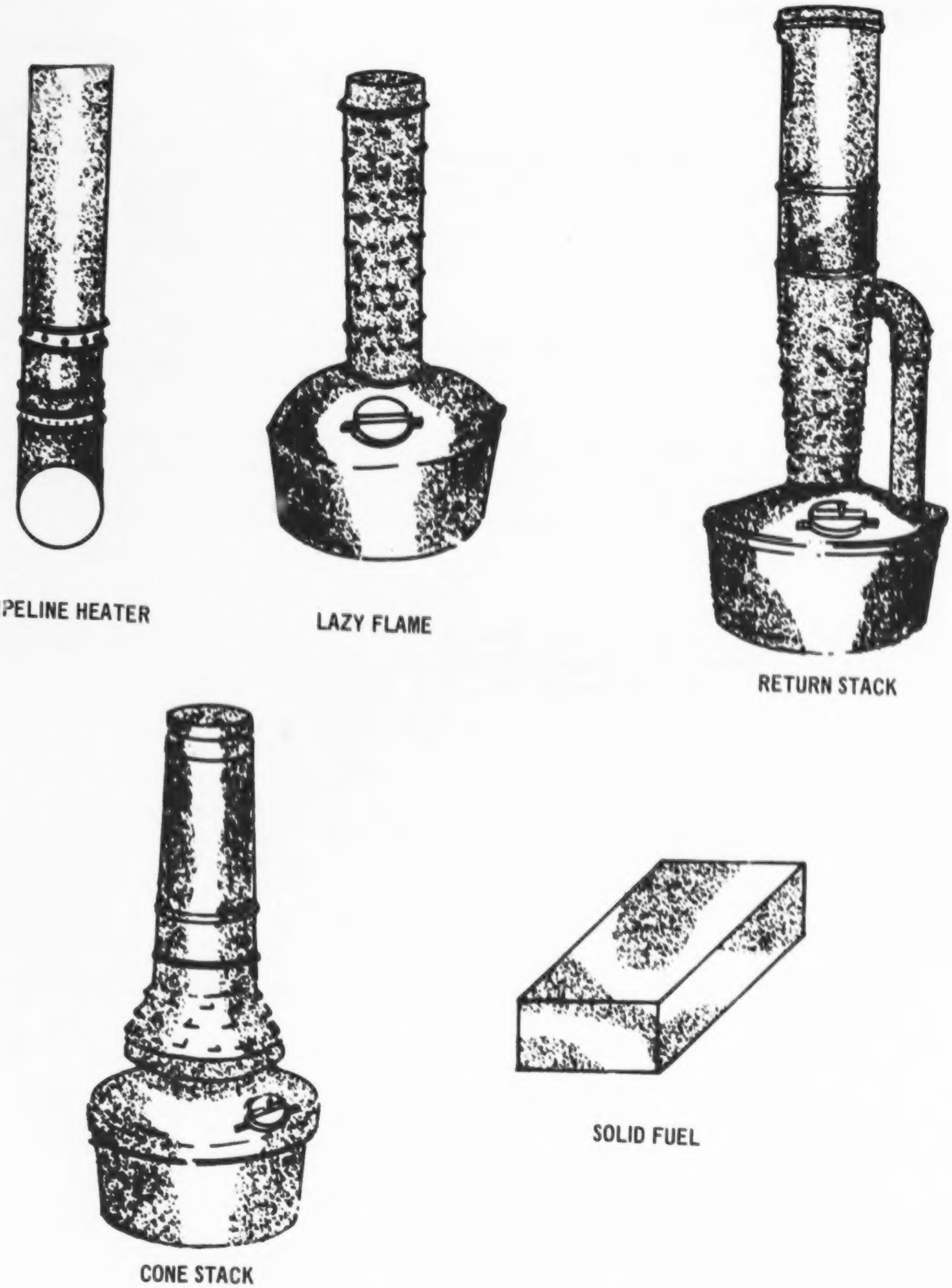
During a heavy thermal inversion, both convective and radiant heating methods are useful in preventing frost damage; there is little difference in the effectiveness of the various heaters. The temperature response for a given fuel rate is about the same for each type of heater as long as the heater is clean and does not leak. When there is little or no thermal inversion, radiant heat provided by pipeline, return stack, or cone heaters is the most effective method for preventing damage.

Proper location of the heaters is essential to the uniformity of the radiant heat distributed among the trees. Heaters are usually located in the center space between four trees and are staggered from one row to the next. Extra heaters are used on the borders of the orchard.

6.9.2 Emissions[1,6]

Emissions from orchard heaters are dependent on the fuel usage rate and the type of heater. Pipeline heaters have the lowest particulate emission rates of all orchard heaters. Hydrocarbon emissions are negligible in the pipeline heaters and in lazy flame, return stack, and cone heaters that have been converted to a pipeline system. Nearly all of the hydrocarbon losses are evaporative losses from fuel contained in the heater reservoir. Because of the low burning temperatures used, nitrogen oxide emissions are negligible.

Emission factors for the different types of orchard heaters are presented in Table 6.9-1 and Figure 6.9-2.



PIPELINE HEATER

LAZY FLAME

RETURN STACK

CONE STACK

SOLID FUEL

Figure 6.9-1. Types of orchard heaters.[6]

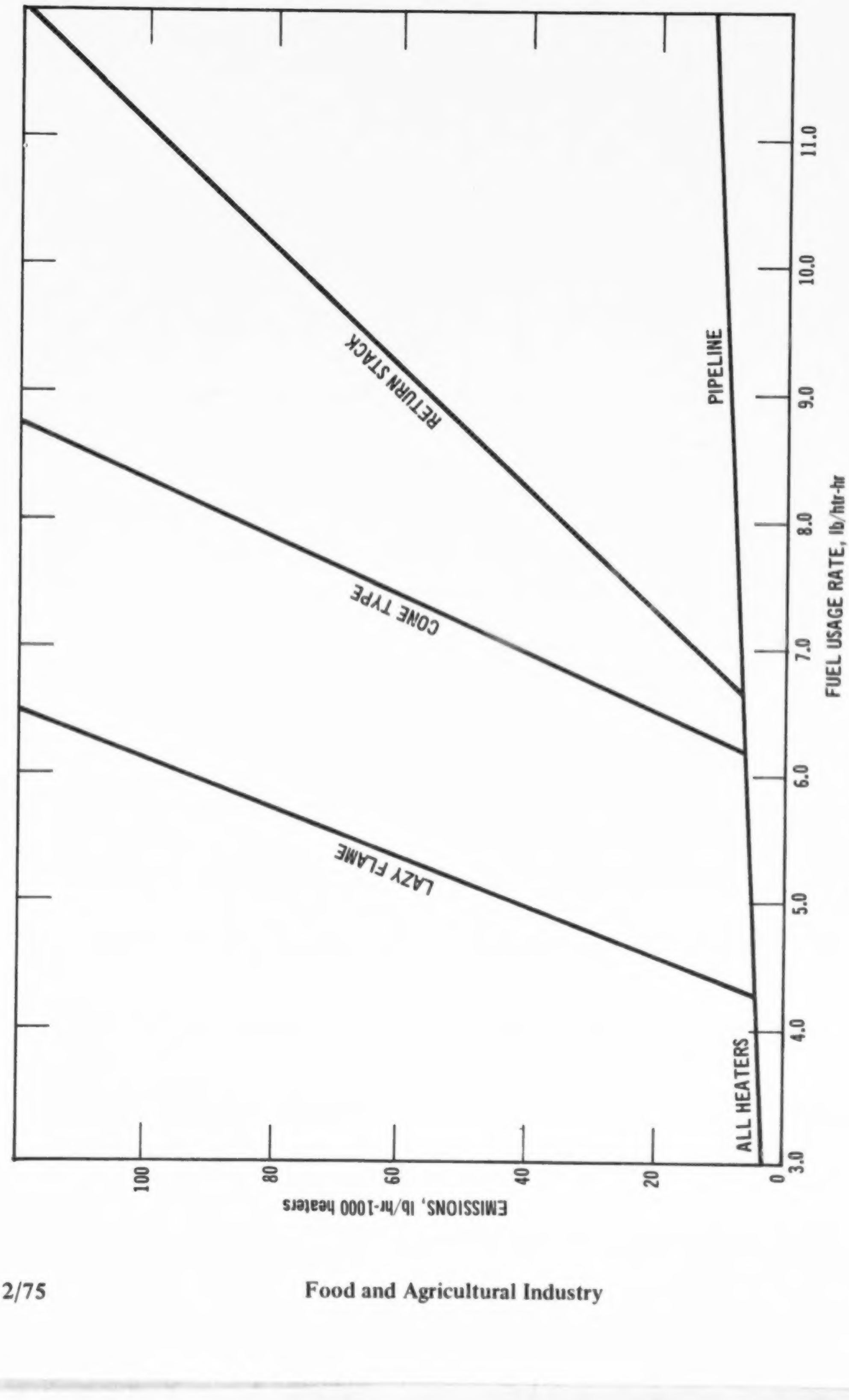


Figure 6.9-2. Particulate emissions from orchard heaters.3,6

Table 6.9-1. EMISSION FACTORS FOR ORCHARD HEATERS[a]
EMISSION FACTOR RATING: C

Pollutant	Type of heater				
	Pipeline	Lazy flame	Return stack	Cone	Solid fuel
Particulate					
lb/htr-hr	b	b	b	b	0.05
kg/htr-hr	b	b	b	b	0.023
Sulfur oxides					
lb/htr-hr	0.13S[d]	0.11S	0.14S	0.14S	NA[e]
kg/htr-hr	0.06S	0.05S	0.06S	0.06S	NA
Carbon monoxide					
lb/htr-hr	6.2	NA	NA	NA	NA
kg/htr-hr	2.8	NA	NA	NA	NA
Hydrocarbons[f]					
lb/htr-yr	Neg[g]	16.0	16.0	16.0	Neg
kg/htr-yr	Neg	7.3	7.3	7.3	Neg
Nitrogen oxides[h]					
lb/htr-hr	Neg	Neg	Neg	Neg	Neg
kg/htr-hr	Neg	Neg	Neg	Neg	Neg

[a] References 1, 3, 4, and 6.

[b] Particulate emissions for pipeline, lazy flame, return stack, and cone heaters are shown in Figure 6.9-2.

[c] Based on emission factors for fuel oil combustion in Section 1.3.

[d] S=sulfur content.

[e] Not available.

[f] Based on emission factors for fuel oil combustion in Section 1.3. Evaporative losses only. Hydrocarbon emissions from combustion are considered negligible. Evaporative hydrocarbon losses for units that are part of a pipeline system are negligible.

[g] Negligible.

[h] Little nitrogen oxide is formed because of the relatively low combustion temperatures.

References for Section 6.9

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2. Frost Protection in Citrus. Agricultural Extension Service, University of California, Ventura. November 1967.
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4. Communication with the Smith Energy Company, Los Angeles, Calif. January 1968.
5. Communication with Agricultural Extension Service, University of California, Ventura, Calif. October 1969.
6. Personal communication with Mr. Ted Wakai. Air Pollution Control District, County of Ventura, Ojai, Calif. May 1972.

6.10 PHOSPHATE FERTILIZERS

Nearly all phosphatic fertilizers are made from naturally occurring, phosphorus-containing minerals such as phosphate rock. Because the phosphorus content of these minerals is not in a form that is readily available to growing plants, the minerals must be treated to convert the phosphorus to a plant-available form. This conversion can be done either by the process of acidulation or by a thermal process. The intermediate steps of the mining of phosphate rock and the manufacture of phosphoric acid are not included in this section as they are discussed in other sections of this publication; it should be kept in mind, however, that large integrated plants may have all of these operations taking place at one location.

In this section phosphate fertilizers have been divided into three categories: (1) normal superphosphate, (2) triple superphosphate, and (3) ammonium phosphate. Emission factors for the various processes involved are shown in Table 6.10-1.

Table 6.10-1. EMISSION FACTORS FOR THE PRODUCTION OF PHOSPHATE FERTILIZERS
EMISSION FACTOR RATING: C

Type of product	Particulates[a]	
	lb/ton	kg/MT
Normal superphosphate[b]		
Grinding, drying	9	4.5
Main stack	–	–
Triple superphosphate[b]		
Run-of-pile (ROP)	–	–
Granular	–	–
Diammonium phosphate[c]		
Dryer, cooler	80	40
Ammoniator-granulator	2	1

[a] Control efficiencies of 99 percent can be obtained with fabric filters.
[b] References 1 through 3.
[c] References 1, 4, and 5 through 8.

6.10.1 Normal Superphosphate

6.10.1.1 General[4,9]–Normal superphosphate (also called single or ordinary superphosphate) is the product resulting from the acidulation of phosphate rock with sulfuric acid. Normal superphosphate contains from 16 to 22 percent phosphoric anhydride (P_2O_5). The physical steps involved in making superphosphate are: (1) mixing rock and acid, (2) allowing the mix to assume a solid form (denning), and (3) storing (curing) the material to allow the acidulation reaction to be completed. After the curing period, the product can be ground and bagged for sale, the cured superphosphate can be sold directly as run-of-pile product, or the material can be granulated for sale as granulated superphosphate.

6.10.1.2 Emissions – The gases released from the acidulation of phosphate rock contain silicon tetrafluoride, carbon dioxide, steam, particulates, and sulfur oxides. The sulfur oxide emissions arise from the reaction of phosphate rock and sulfuric acid.[10]

If a granulated superphosphate is produced, the vent gases from the granulator-ammoniator may contain particulates, ammonia, silicon tetrafluoride, hydrofluoric acid, ammonium chloride, and fertilizer dust. Emissions from the final drying of the granulated product will include gaseous and particulate fluorides, ammonia, and fertilizer dust.

6.10.2 Triple Superphosphate

6.10.2.1 General[4,9]–Triple superphosphate (also called double or concentrated superphosphate) is the product resulting from the reaction between phosphate rock and phosphoric acid. The product generally contains 44 to 52 percent P_2O_5, which is about three times the P_2O_5 usually found in normal superphosphates.

Presently, there are three principal methods of manufacturing triple superphosphate. One of these uses a cone mixer to produce a pulverized product that is particularly suited to the manufacture of ammoniated fertilizers. This product can be sold as run-of-pile (ROP), or it can be granulated. The second method produces in a multi-step process a granulated product that is well suited for direct application as a phosphate fertilizer. The third method combines the features of quick drying and granulation in a single step.

6.10.2.2 Emissions–Most triple superphosphate is the nongranular type. The exit gases from a plant producing the nongranular product will contain considerable quantities of silicon tetrafluoride, some hydrogen fluoride, and a small amount of particulates. Plants of this type also emit fluorides from the curing buildings.

In the cases where ROP triple superphosphate is granulated, one of the greatest problems is the emission of dust and fumes from the dryer and cooler. Emissions from ROP granulation plants include silicon tetrafluoride, hydrogen fluoride, ammonia, particulate matter, and ammonium chloride.

In direct granulation plants, wet scrubbers are usually used to remove the silicon tetrafluoride and hydrogen fluoride generated from the initial contact between the phosphoric acid and the dried rock. Screening stations and bagging stations are a source of fertilizer dust emissions in this type of process.

6.10.3 AMMONIUM PHOSPHATE

6.10.3.1 General–The two general classes of ammonium phosphates are monammonium phosphate and diammonium phosphate. The production of these types of phosphate fertilizers is starting to displace the production of other phosphate fertilizers because the ammonium phosphates have a higher plant food content and a lower shipping cost per unit weight of P_2O_5.

There are various processes and process variations in use for manufacturing ammonium phosphates. In general, phosphoric acid, sulfuric acid, and anhydrous ammonia are allowed to react to produce the desired grade of ammonium phosphate. Potash salts are added, if desired, and the product is granulated, dried, cooled, screened, and stored.

6.10.3.2 Emissions–The major pollutants from ammonium phosphate production are fluoride, particulates, and ammonia. The largest sources of particulate emissions are the cage mills, where oversized products from the screens are ground before being recycled to the ammoniator. Vent gases from the ammoniator tanks are the major source of ammonia. This gas is usually scrubbed with acid, however, to recover the residual ammonia.

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6.11 STARCH MANUFACTURING

6.11.1 Process Description[1]

The basic raw material in the manufacture of starch is dent corn, which contains starch. The starch in the corn is separated from the other components by "wet milling."

The shelled grain is prepared for milling in cleaners that remove both the light chaff and any heavier foreign material. The cleaned corn is then softened by soaking (steeping) it in warm water acidified with sulfur dioxide. The softened corn goes through attrition mills that tear the kernels apart, freeing the germ and loosening the hull. The remaining mixture of starch, gluten, and hulls is finely ground, and the coarser fiber particles are removed by screening. The mixture of starch and gluten is then separated by centrifuges, after which the starch is filtered and washed. At this point it is dried and packaged for market.

6.11.2 Emissions

The manufacture of starch from corn can result in significant dust emissions. The various cleaning, grinding, and screening operations are the major sources of dust emissions. Table 6.11-1 presents emission factors for starch manufacturing.

Table 6.11-1. EMISSION FACTORS FOR STARCH MANUFACTURING[a]
EMISSION FACTOR RATING: D

Type of operation	Particulates	
	lb/ton	kg/MT
Uncontrolled	8	4
Controlled[b]	0.02	0.01

[a] Reference 2.

[b] Based on centrifugal gas scrubber.

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6.12 SUGAR CANE PROCESSING

revised by Tom Lahre

6.12.1 General [1-3]

Sugar cane is burned in the field prior to harvesting to remove unwanted foliage as well as to control rodents and insects. Harvesting is done by hand or, where possible, by mechanical means.

After harvesting, the cane goes through a series of processing steps for conversion to the final sugar product. It is first washed to remove dirt and trash; then crushed and shredded to reduce the size of the stalks. The juice is next extracted by one of two methods, milling or diffusion. In milling, the cane is pressed between heavy rollers to squeeze out the juice; in diffusion, the sugar is leached out by water and thin juices. The raw sugar then goes through a series of operations including clarification, evaporation, and crystallization in order to produce the final product. The fibrous residue remaining after sugar extraction is called bagasse.

All mills fire some or all of their bagasse in boilers to provide power necessary in their milling operation. Some, having more bagasse than can be utilized internally, sell the remainder for use in the manufacture of various chemicals such as furfural.

6.12.2 Emissions [2,3]

The largest sources of emissions from sugar cane processing are the openfield burning in the harvesting of the crop and the burning of bagasse as fuel. In the various processes of crushing, evaporation, and crystallization, relatively small quantities of particulates are emitted. Emission factors for sugar cane field burning are shown in Table 2.4-2. Emission factors for bagasse firing in boilers will be included in Chapter 1 in a future supplement.

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